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Hosseini

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(54) **ELECTRONIC DEVICE WITH ANTENNA ELEMENTS THAT FOLLOW MEANDERING PATTERNS FOR RECEIVING WIRELESS POWER FROM A NEAR-FIELD ANTENNA**

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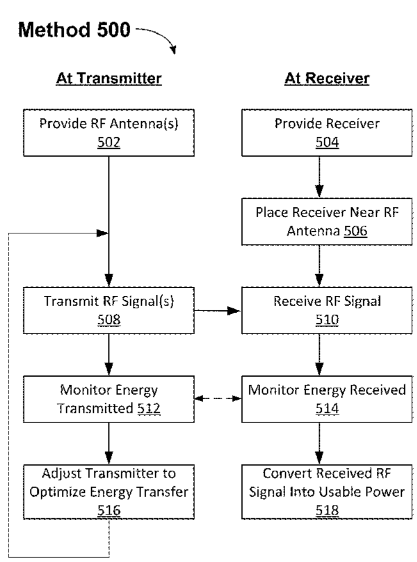
(57) **ABSTRACT**

Systems and methods for receiving near-field wireless power at an electronic device. An electronic device includes a receiver with one or more receiving antenna elements formed by respective conductive lines in a meandering pattern. Each receiving antenna element is configured to receive near-field radio-frequency signals radiated from a transmitting antenna element of a near-field power transmitter. The receiving antenna elements are configured to receive the near-field radio-frequency signals radiated from the transmitting antenna element of the near-field power transmitter when the electronic device is on a surface of the near-field power transmitter, and the transmitting antenna element is formed by respective conductive lines in a meandering pattern. The transmitting antenna element is selectively activated from among a plurality of available transmitting antenna elements of the near-field transmitter. A power-harvesting circuit of the receiver is configured to convert the near-field radio-frequency signals into usable power for the electronic device.

48 Claims, 56 Drawing Sheets
(9 of 56 Drawing Sheet(s) Filed in Color)



Related U.S. Application Data

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See application file for complete search history.

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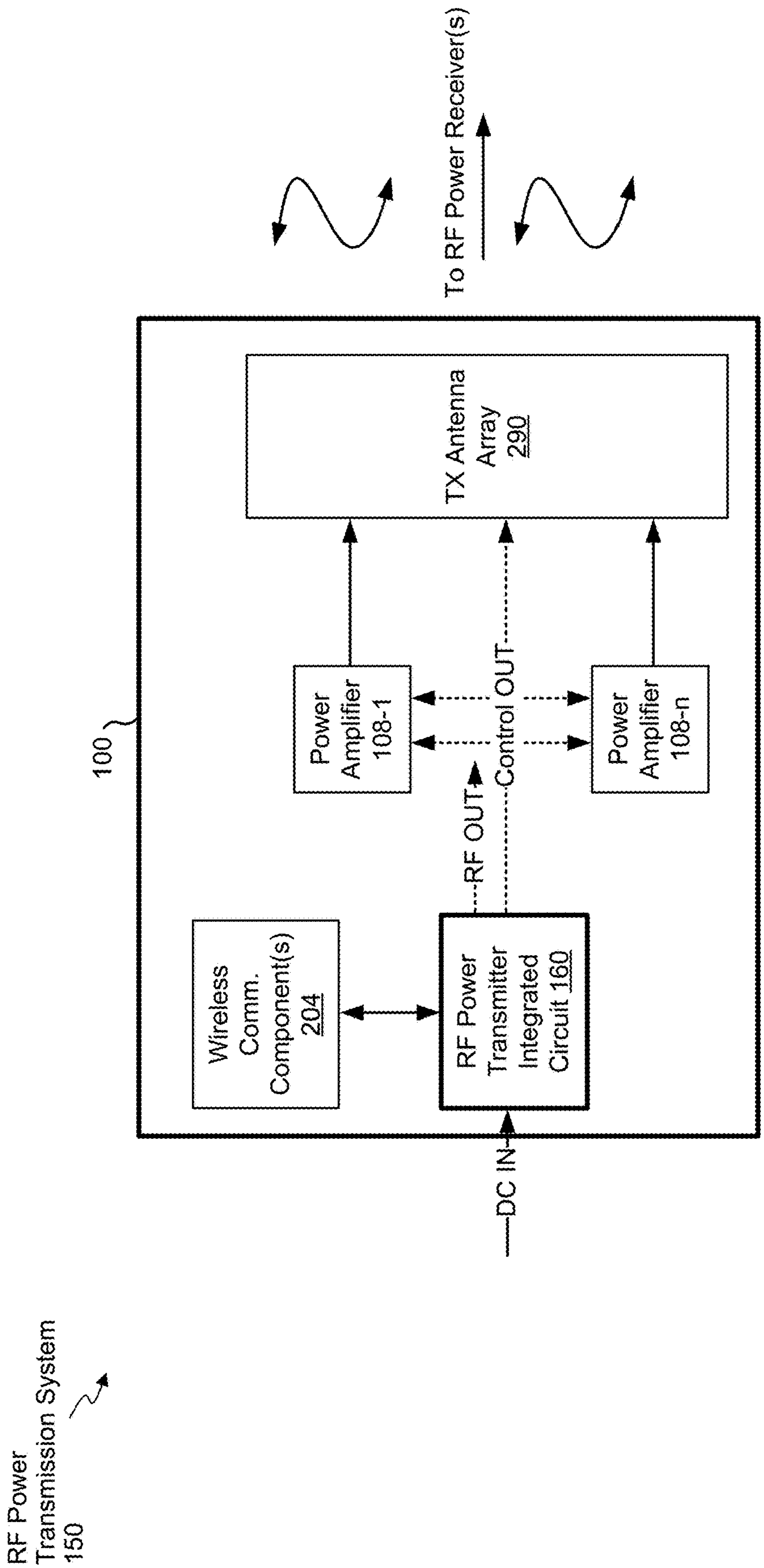
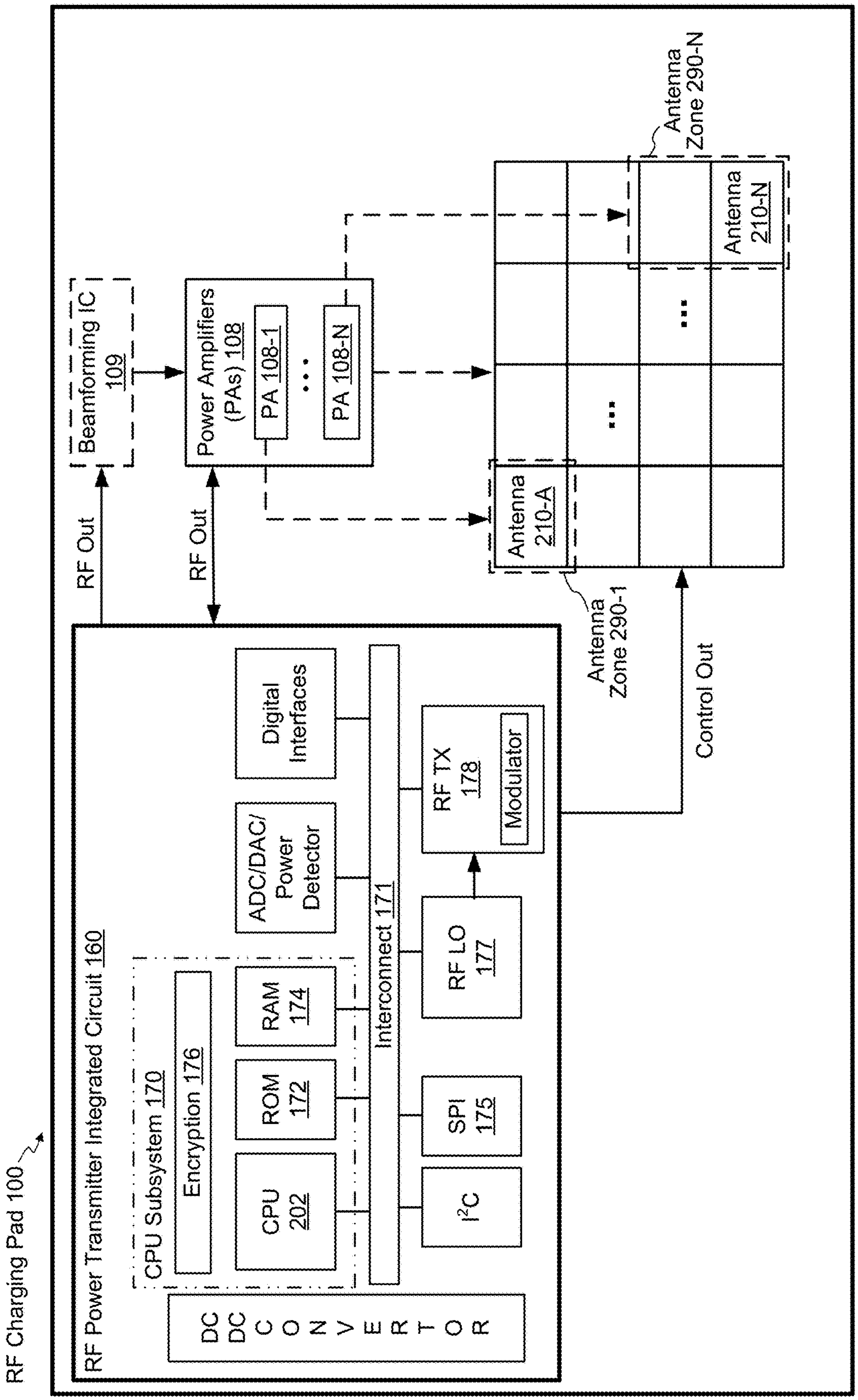


To RF Power Receiver(s)
100
TX Antenna Array 290
Power Amplifier 108-1
Power Amplifier 108-n
Control OUT
RF OUT
Wireless Comm. Component(s) 204
RF Power Transmitter Integrated Circuit 160
DC IN
RF Power Transmission System 150

Figure 1A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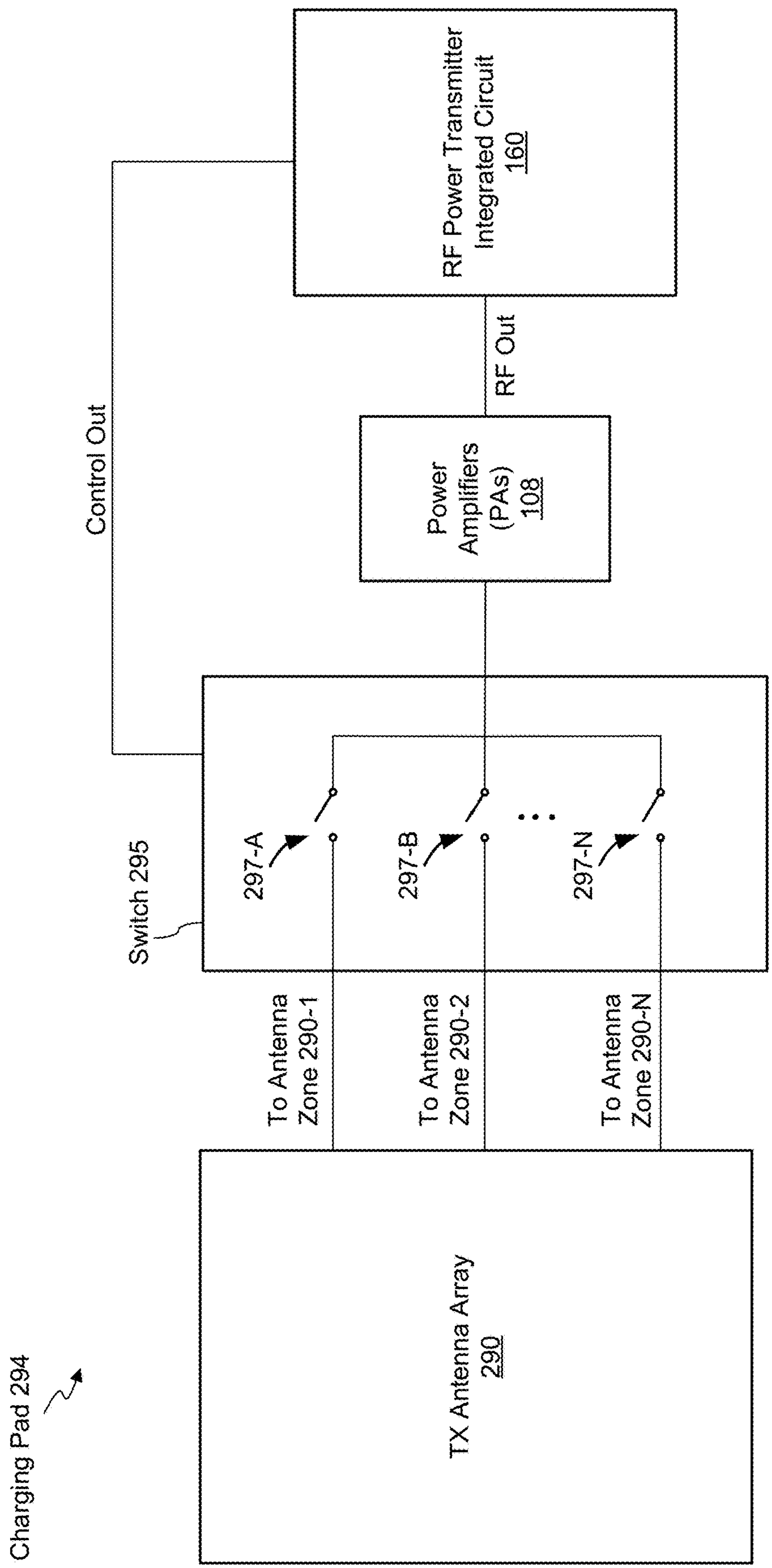
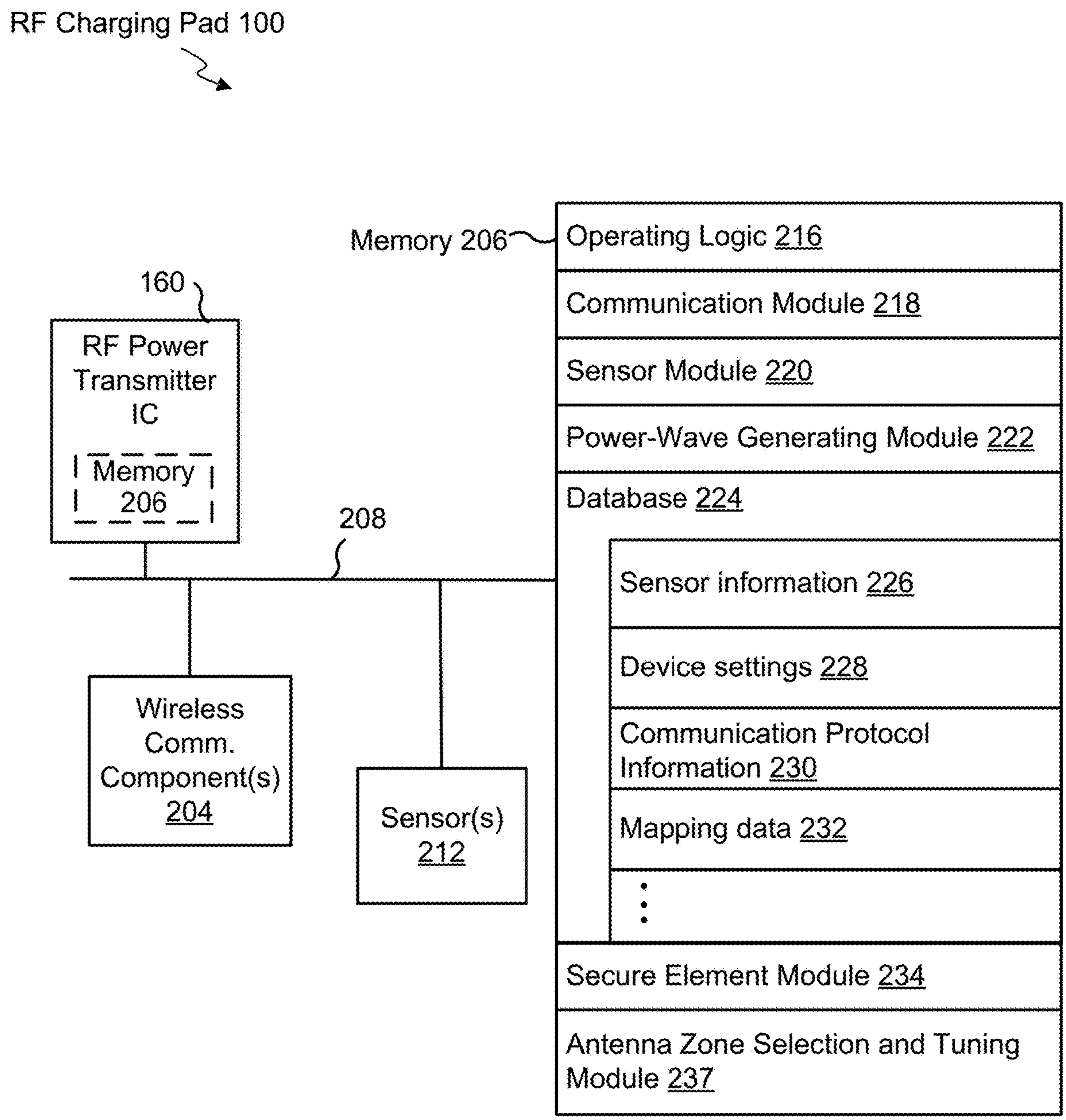
RF Power Transmitter Integrated Circuit 160
DC DC CONVERTOR
CPU Subsystem 170
Encryption 176
CPU 202
ROM 172
RAM 174
Interconnect 171
ADC/DAC/ Power Detector
Digital Interfaces
I2C
SPI 175
RF LO 177
RF TX 178
Modulator
RF Out
RF Out
Beamforming IC 109
Power Amplifiers (PAs) 108
PA 108-1
PA 108-N
Antenna 210-A
Antenna 210-N
Antenna Zone 290-1
Antenna Zone 290-N
Control Out

Figure 1B



RF Power Transmitter Integrated Circuit 160
Control Out
RF Out
Power Amplifiers (PAs) 108
Switch 295
297-A
297-B
297-N
To Antenna Zone 290-1
To Antenna Zone 290-2
To Antenna Zone 290-N
TX Antenna Array 290
Charging Pad 294

FIGURE 1C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Memory 206
Operating Logic 216
Communication Module 218
Sensor Module 220
Power-Wave Generating Module 222
Database 224
Sensor information 226
Device settings 228
Communication Protocol Information 230
Mapping data 232
Secure Element Module 234
Antenna Zone Selection and Tuning Module 237
160
RF Power Transmitter IC
Memory 206
208
Wireless Comm. Component(s) 204
Sensor(s) 212

Figure 2A

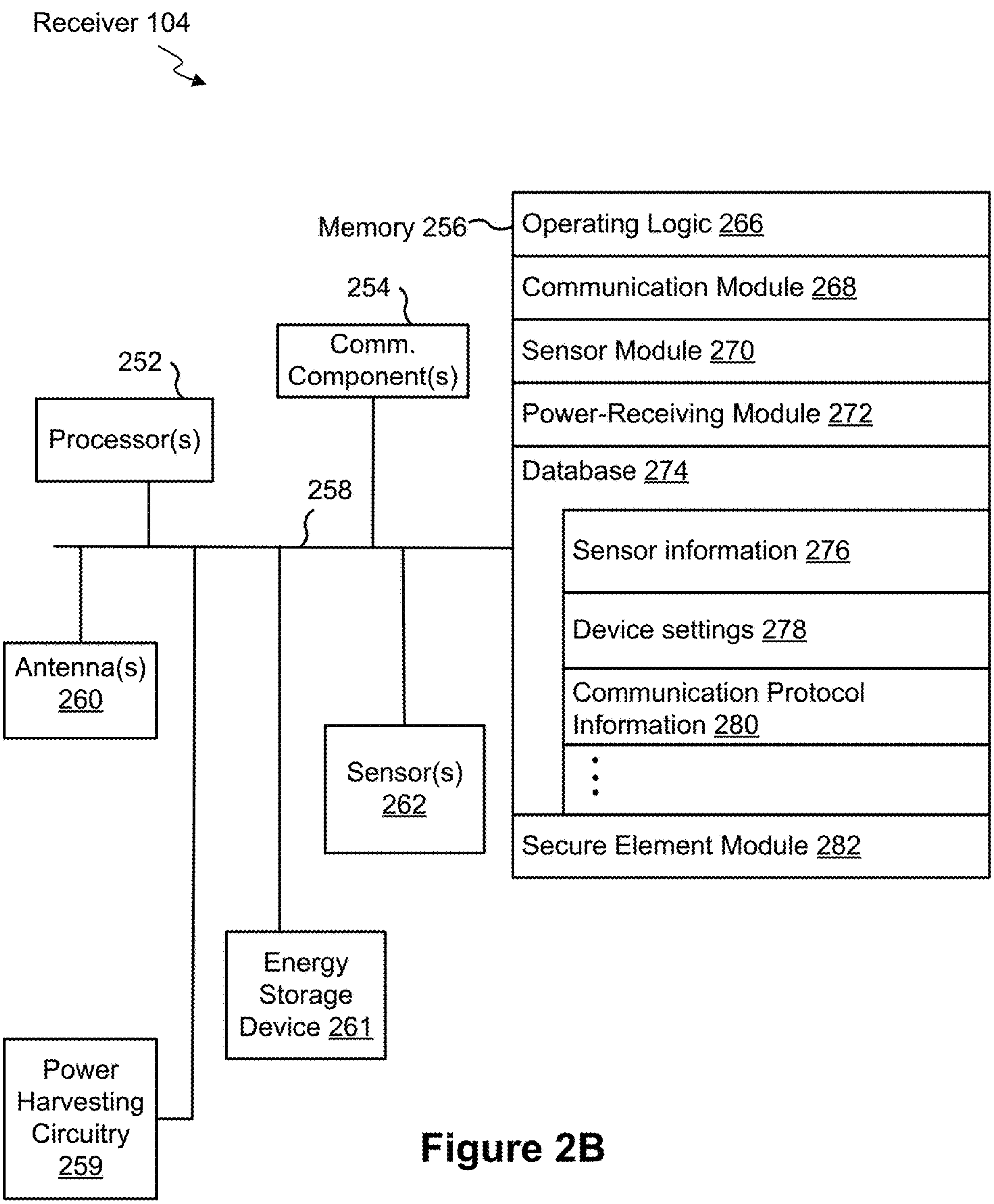
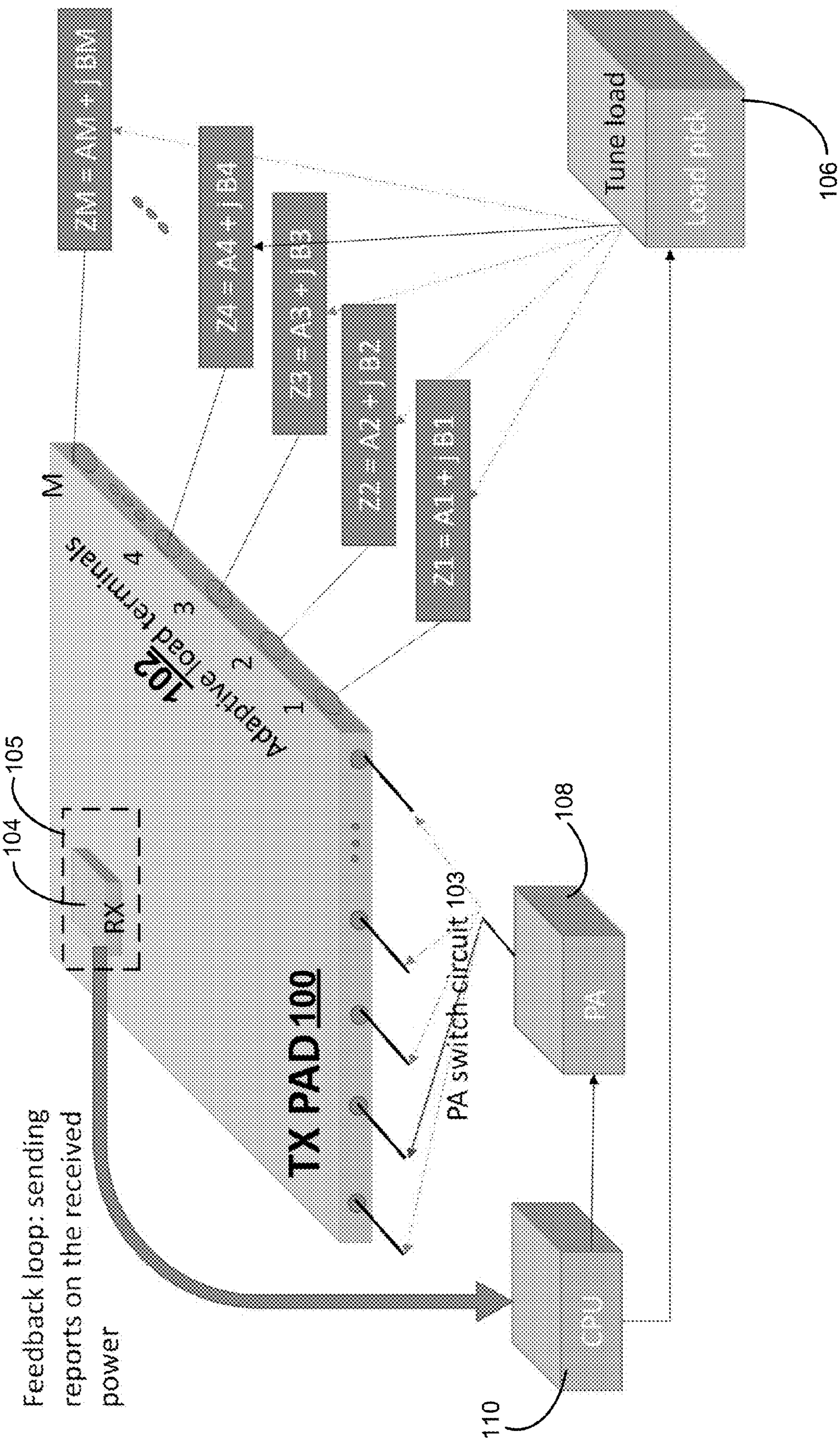

Receiver 104
Memory 256
Operating Logic 266
Communication Module 268
Sensor Module 270
Power-Receiving Module 272
Database 274
Sensor information 276
Device settings 278
Communication Protocol Information 280
Secure Element Module 282
254
Comm. Component(s)
252
Processor(s)
258
Antenna(s) 260
Sensor(s) 262
Energy Storage Device 261
Power Harvesting Circuitry 259

Figure 2B



Z1 = A1 + J B1
Z2 = A2 + J B2
Z3 = A3 + J B3
Z4 = A4 + J B4
ZM = AM + J BM
Tune load
Load pick
106
M
4
3
2
1
Adaptive load terminals
102
105
104
RX
TX PAD 100
PA switch circuit 103
108
PA
Feedback loop: sending reports on the received power
CPU
110

Figure 3A

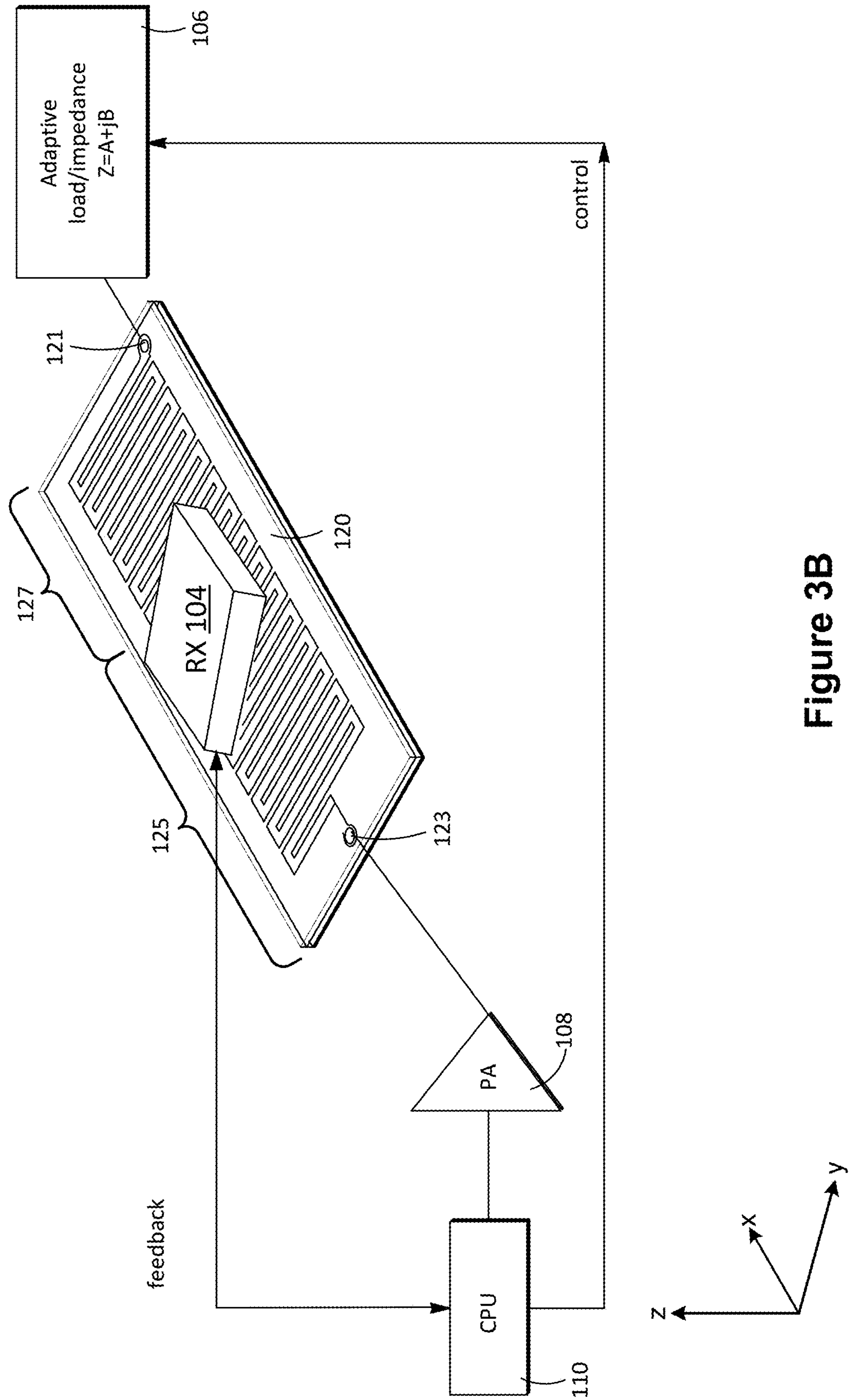

Adaptive
load/impedance
Z=A+jB
106
control
121
127
120
RX 104
125
123
108
PA
feedback
CPU
110
x
y
z

Figure 3B

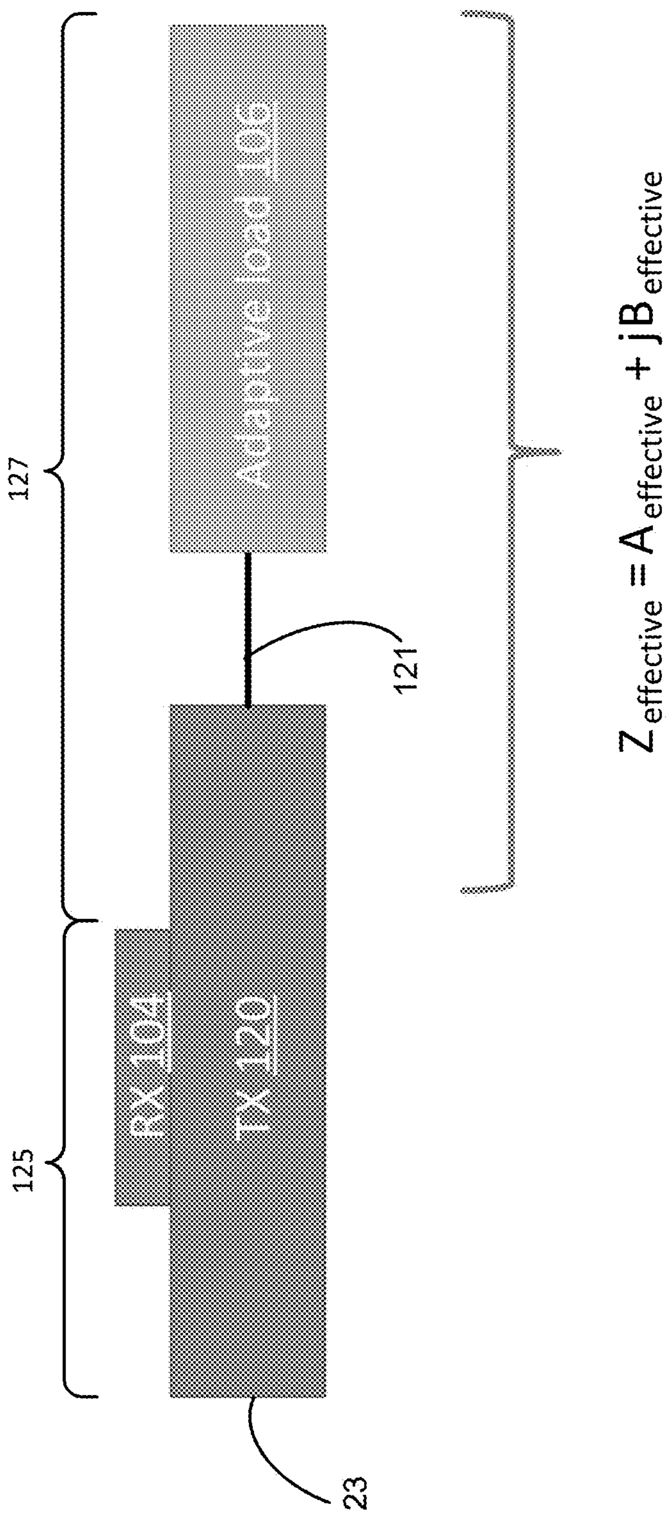

127
125
Adaptive load 106
RX 104
TX 120
121
123
$Z_{effective} = A_{effective} + jB_{effective}$

Figure 3C

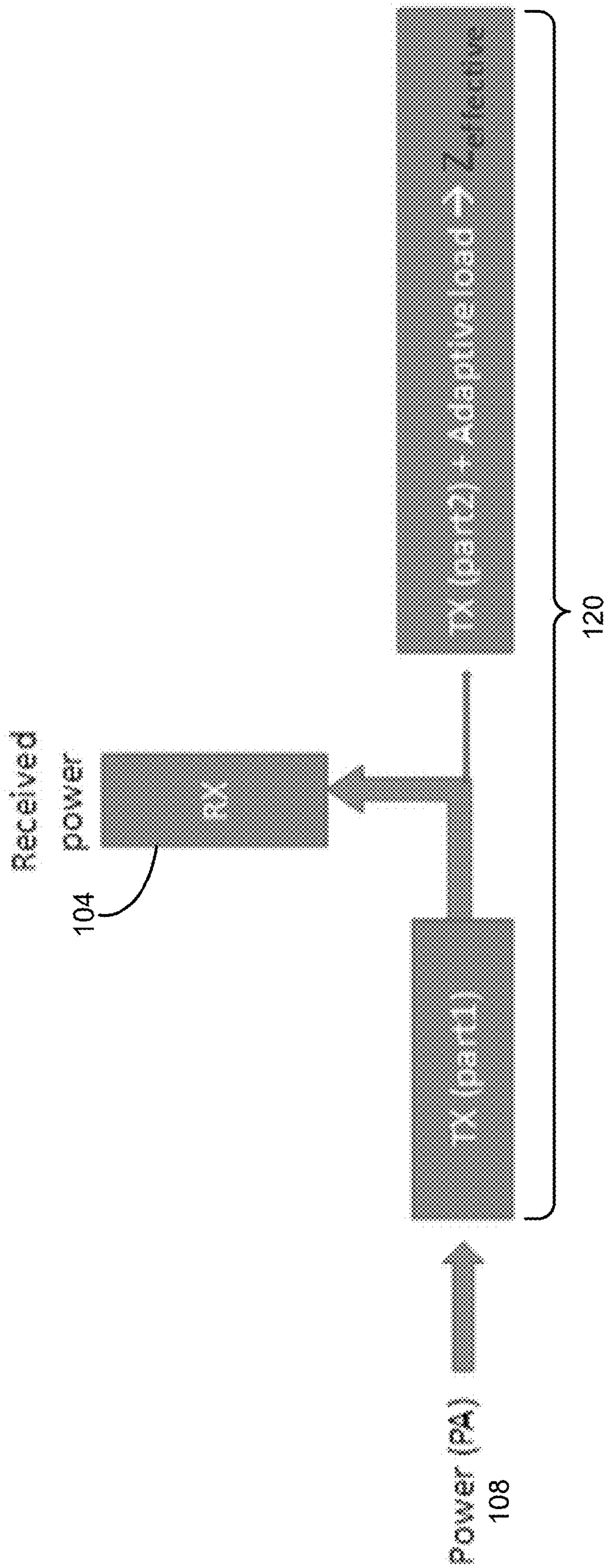

TX (part2) + Adaptive load → Z effective
120
Received power
RX
104
TX (part1)
Power (PA)
108

Figure 3D

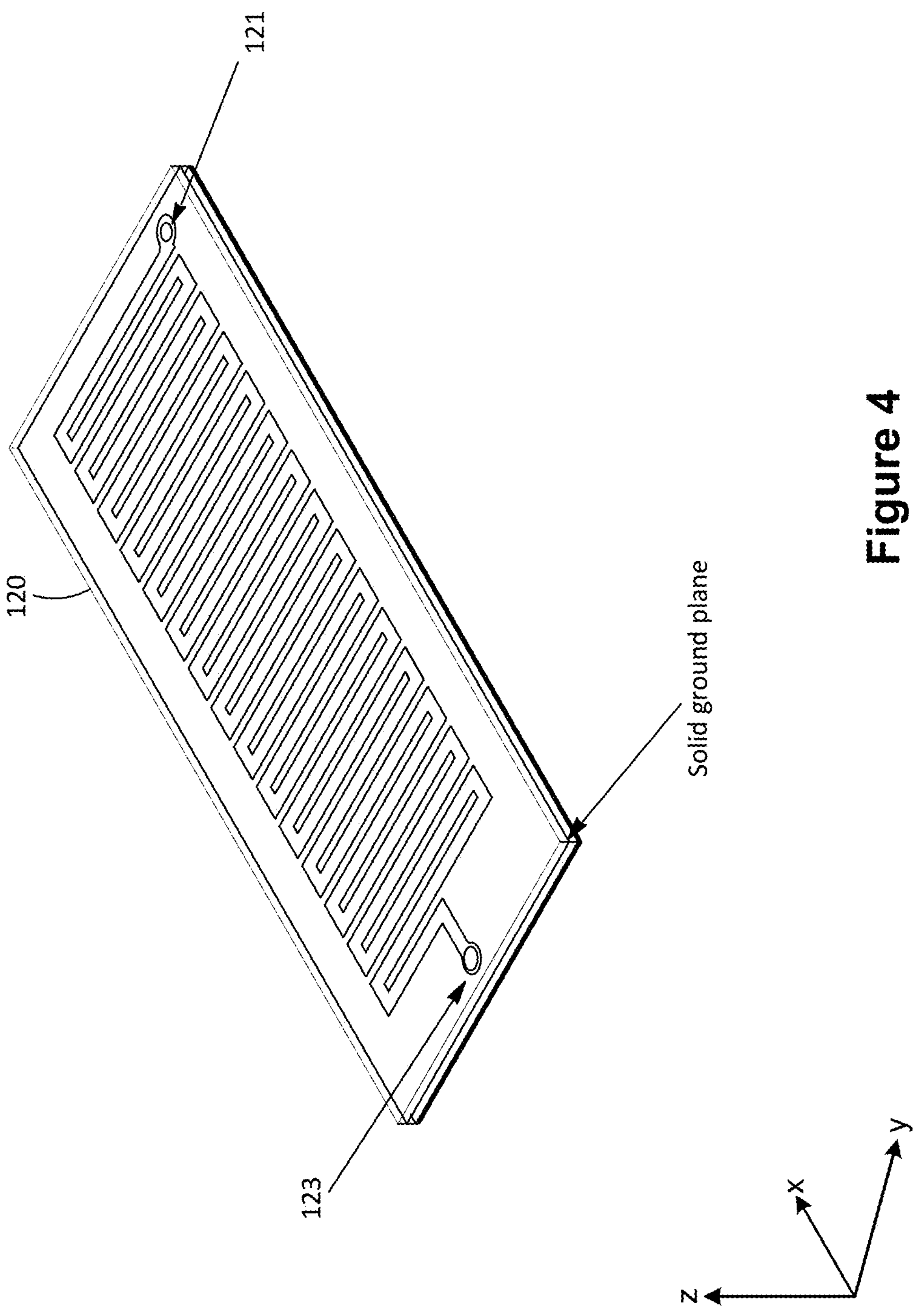


Figure 4

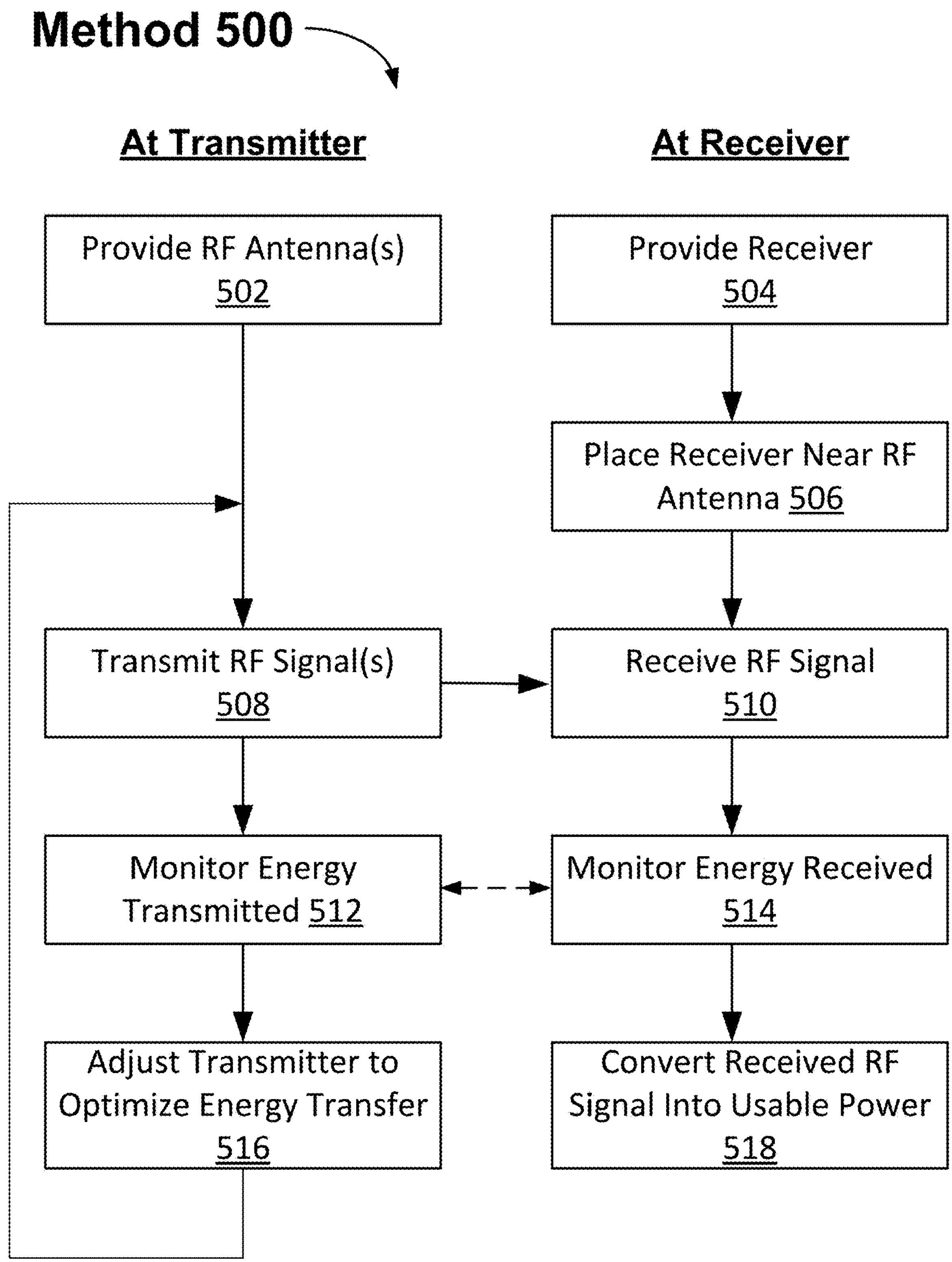

Method 500
At Transmitter
At Receiver
Provide RF Antenna(s) 502
Provide Receiver 504
Place Receiver Near RF Antenna 506
Transmit RF Signal(s) 508
Receive RF Signal 510
Monitor Energy Transmitted 512
Monitor Energy Received 514
Adjust Transmitter to Optimize Energy Transfer 516
Convert Received RF Signal Into Usable Power 518

Figure 5

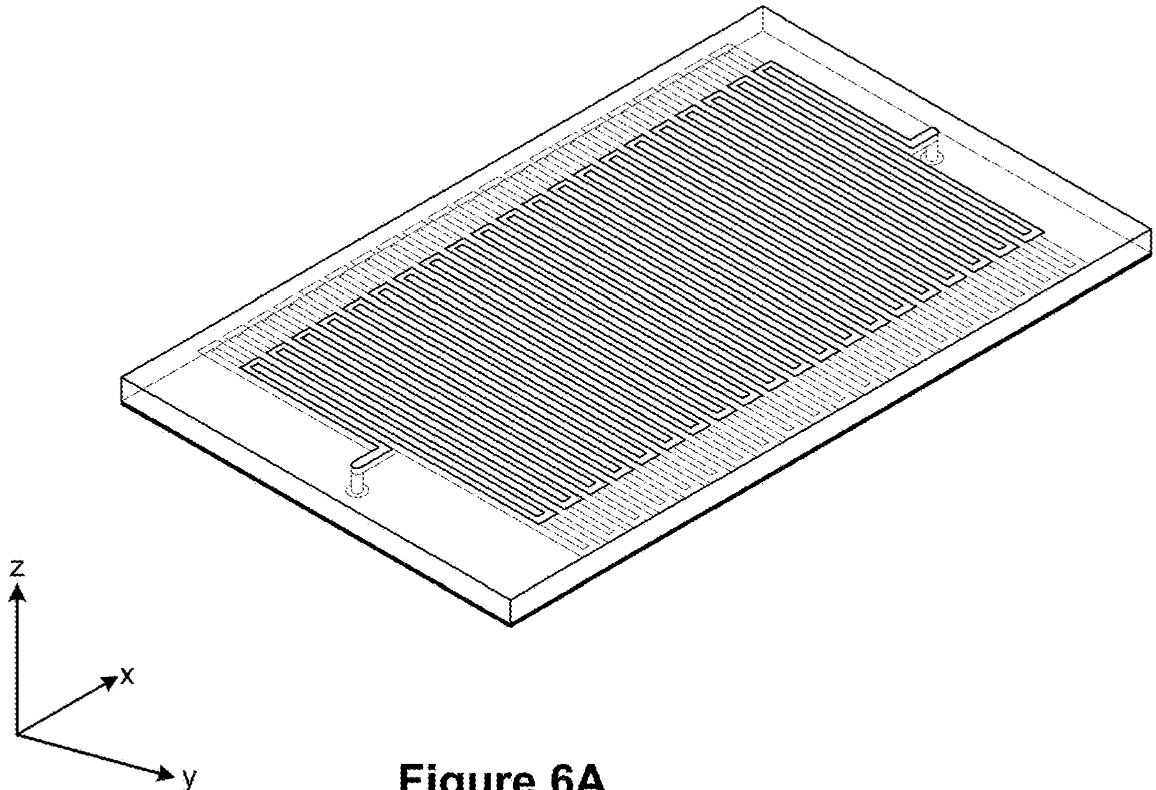


Figure 6A

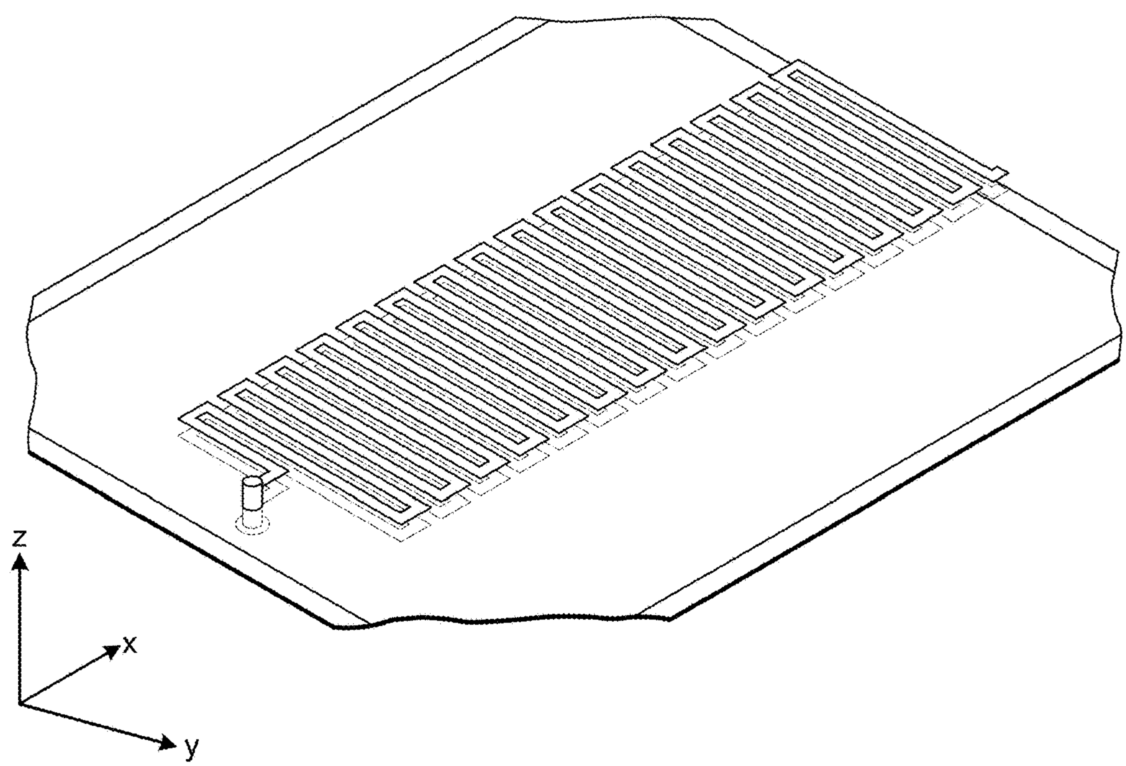


Figure 6B

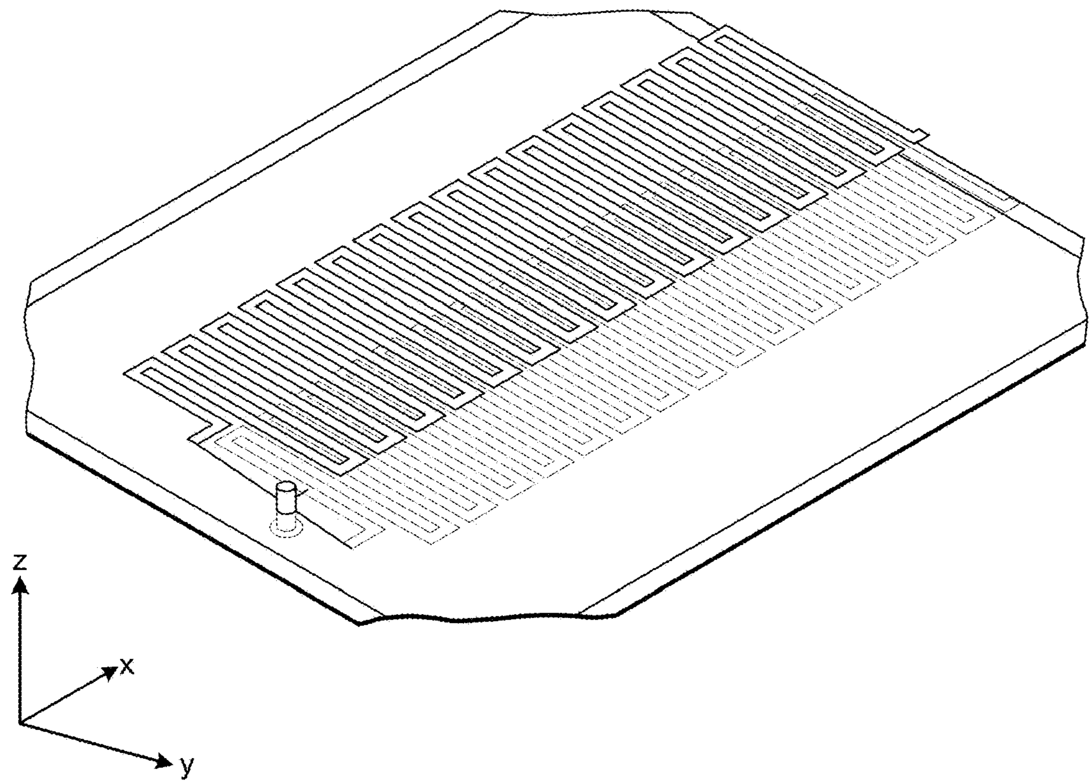


Figure 6C

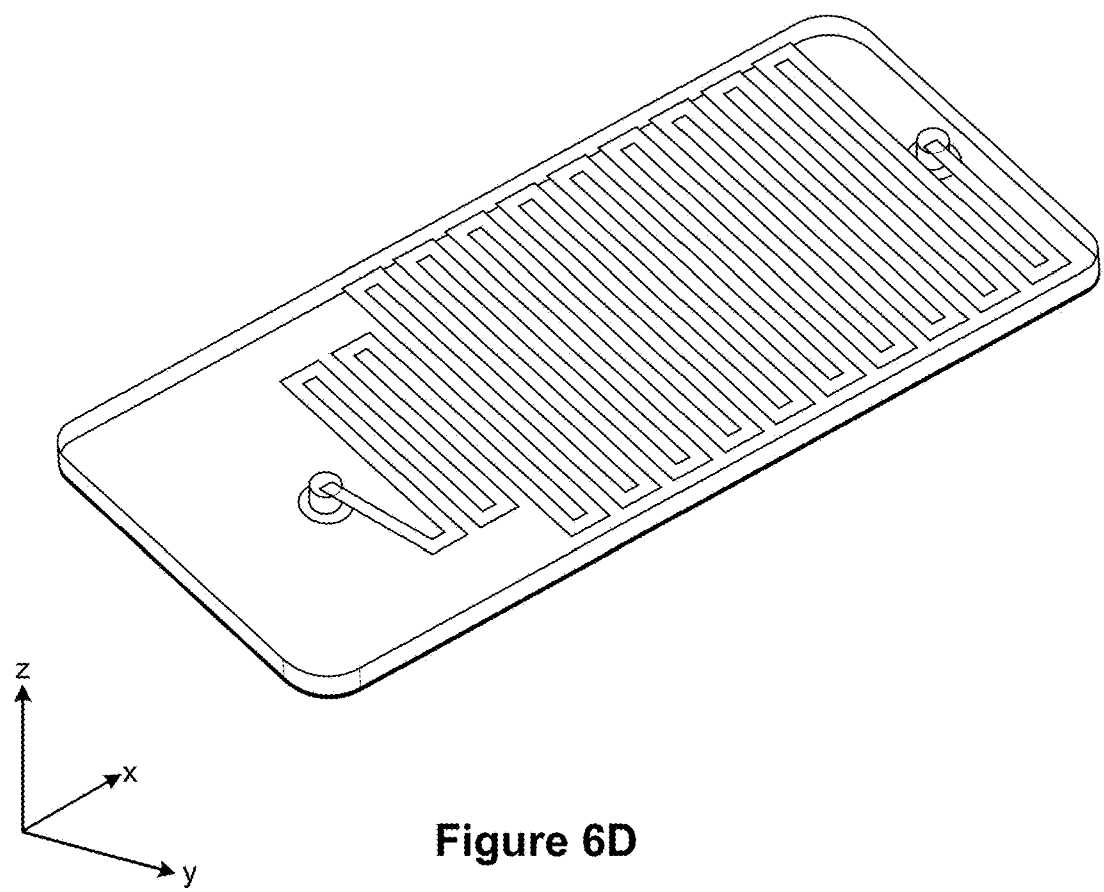


Figure 6D

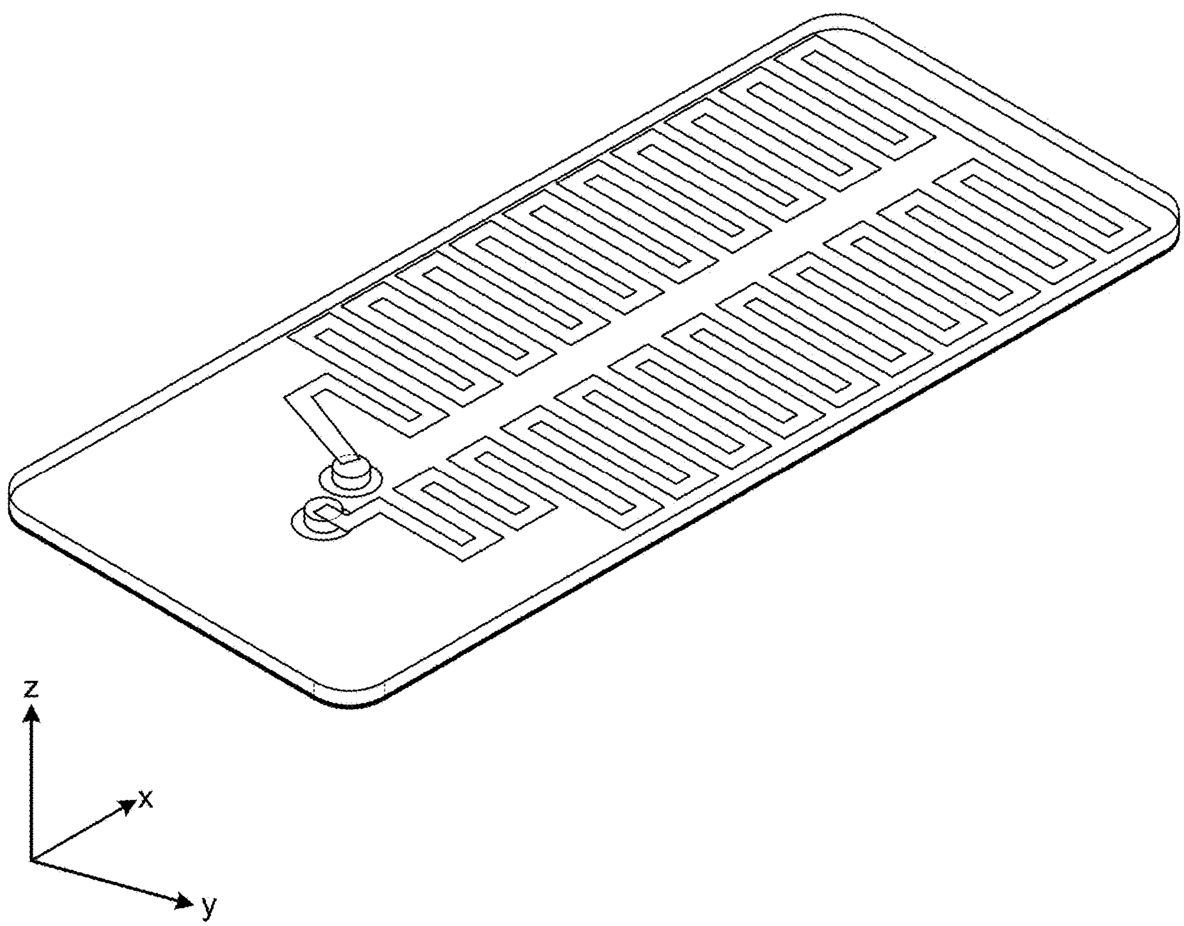


Figure 6E

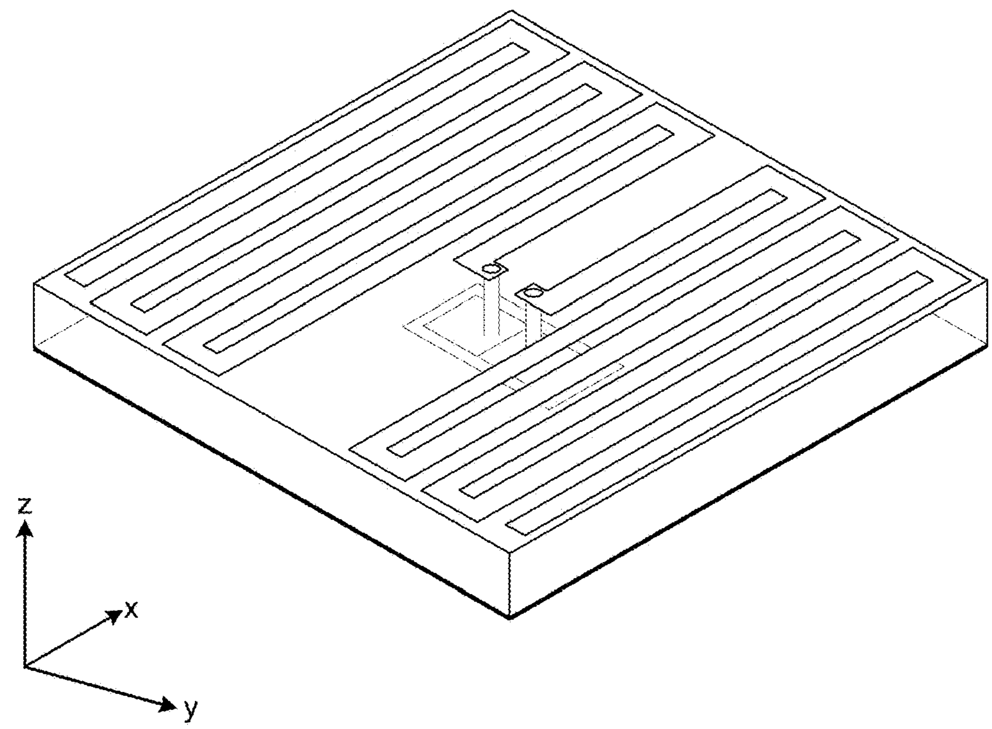


Figure 7A

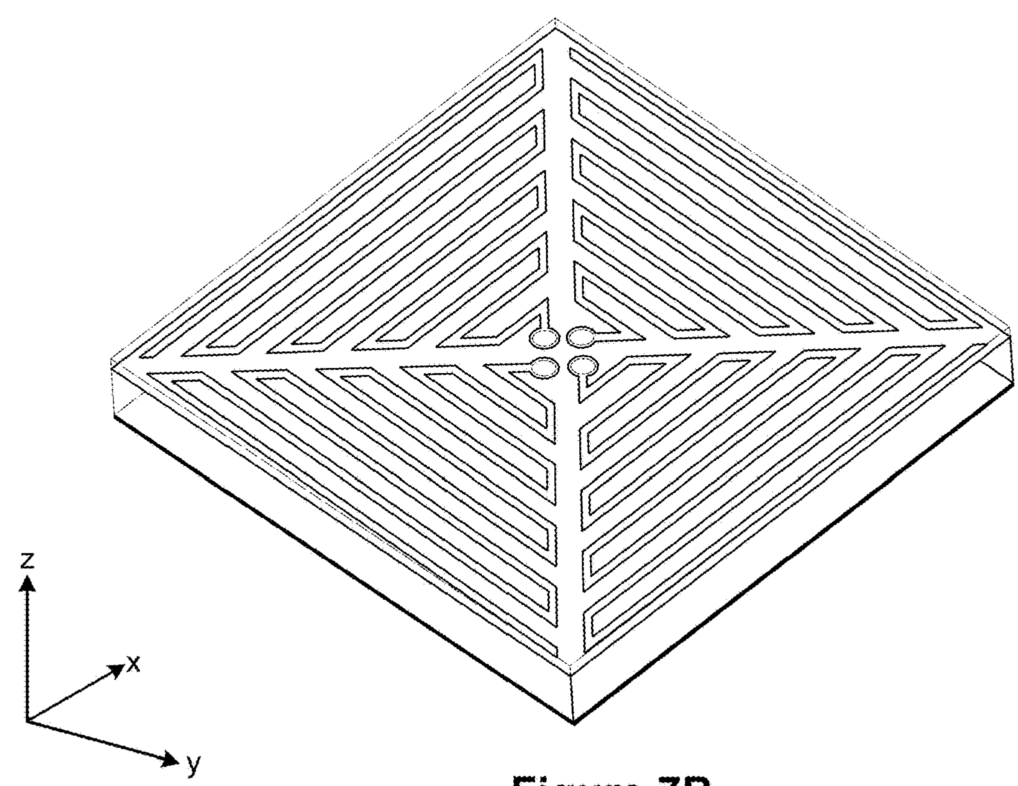


Figure 7B

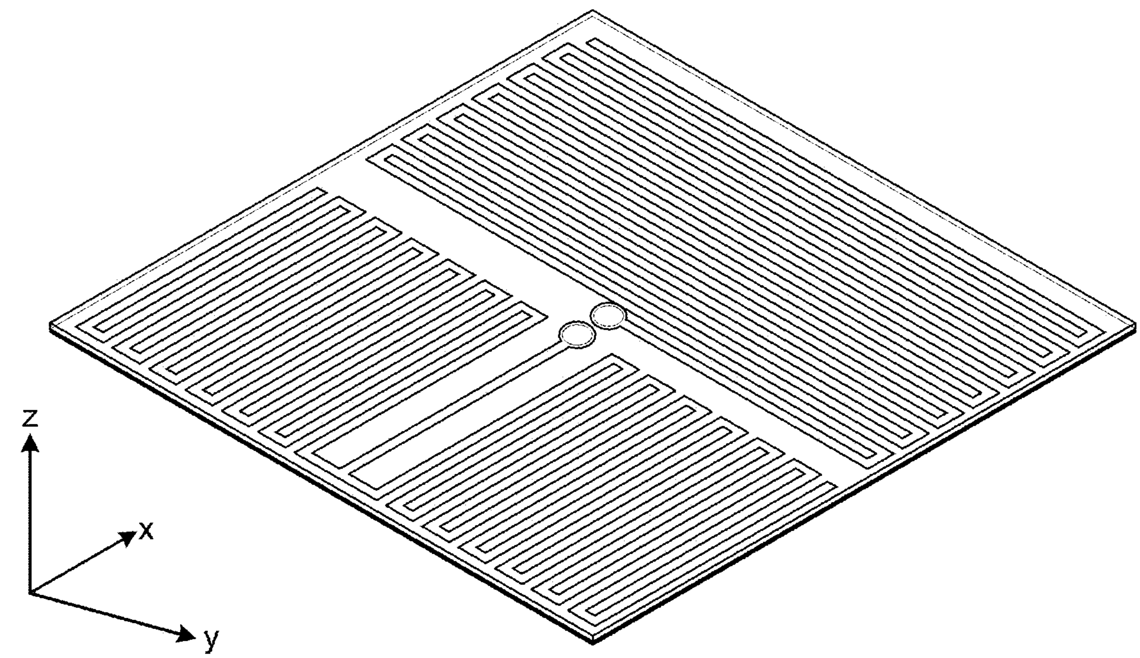


Figure 7C

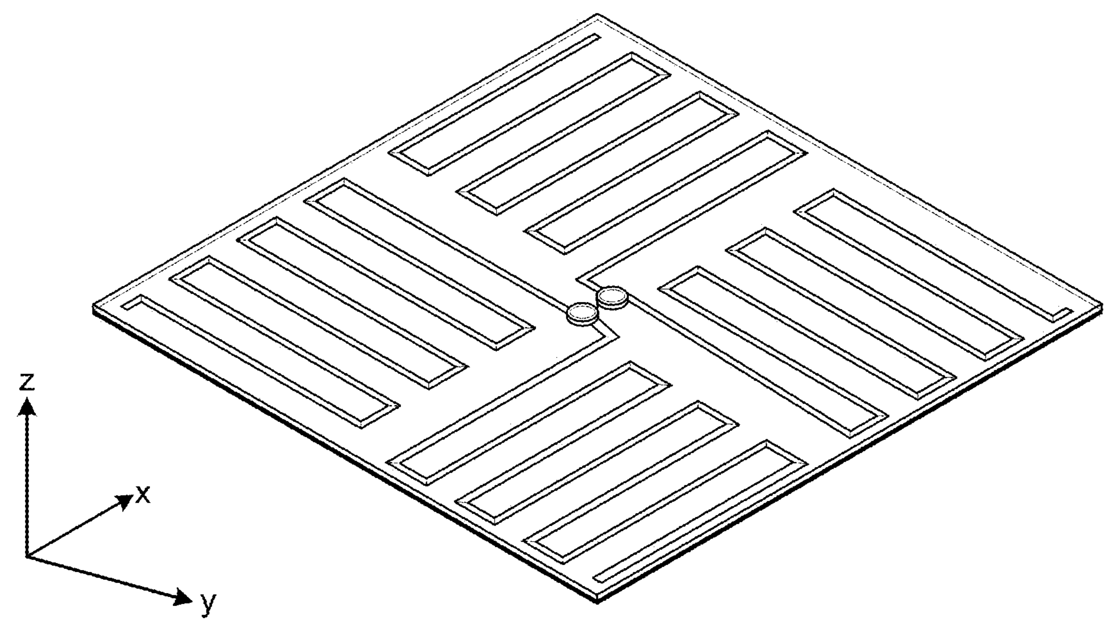


Figure 7D

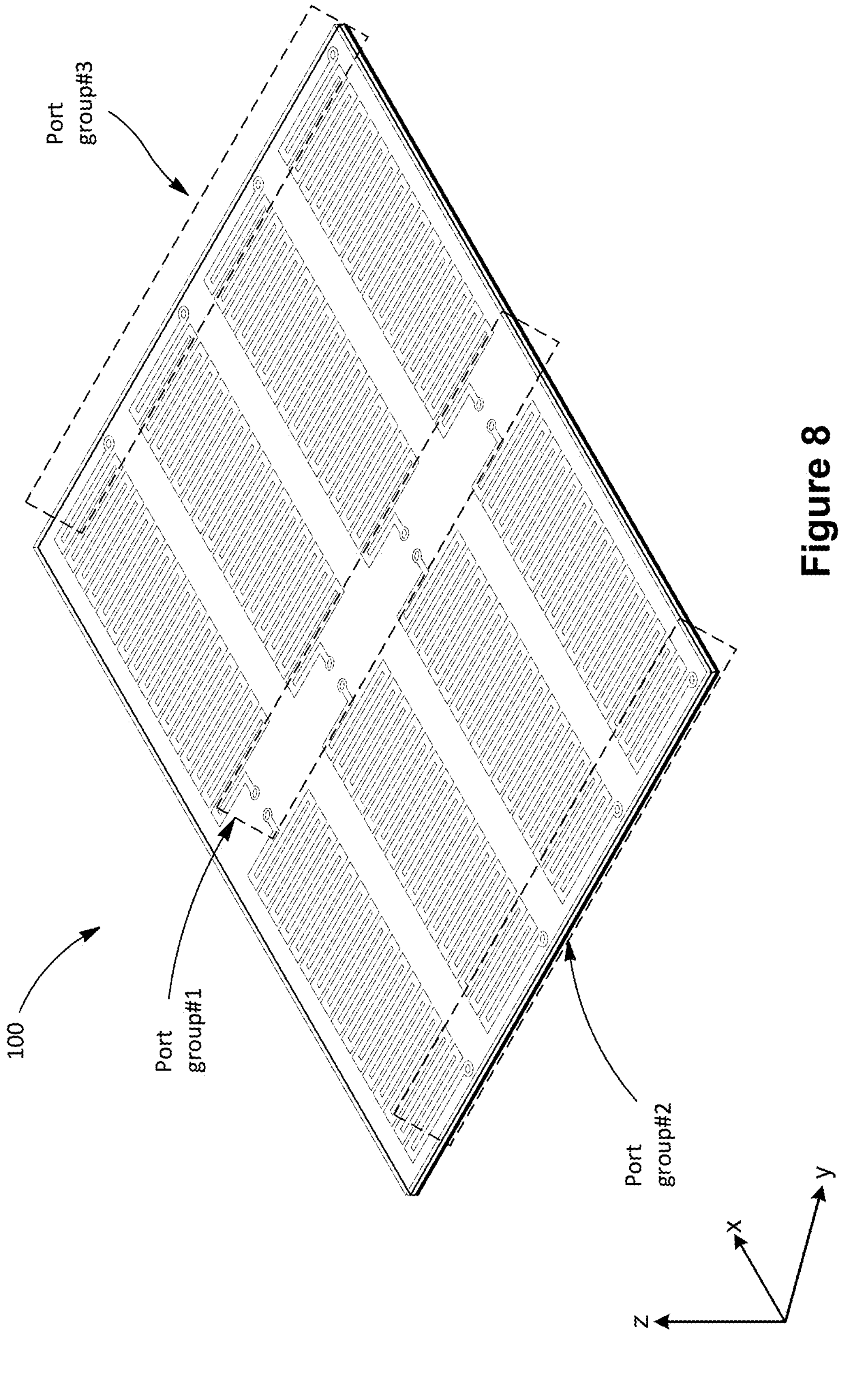


Figure 8

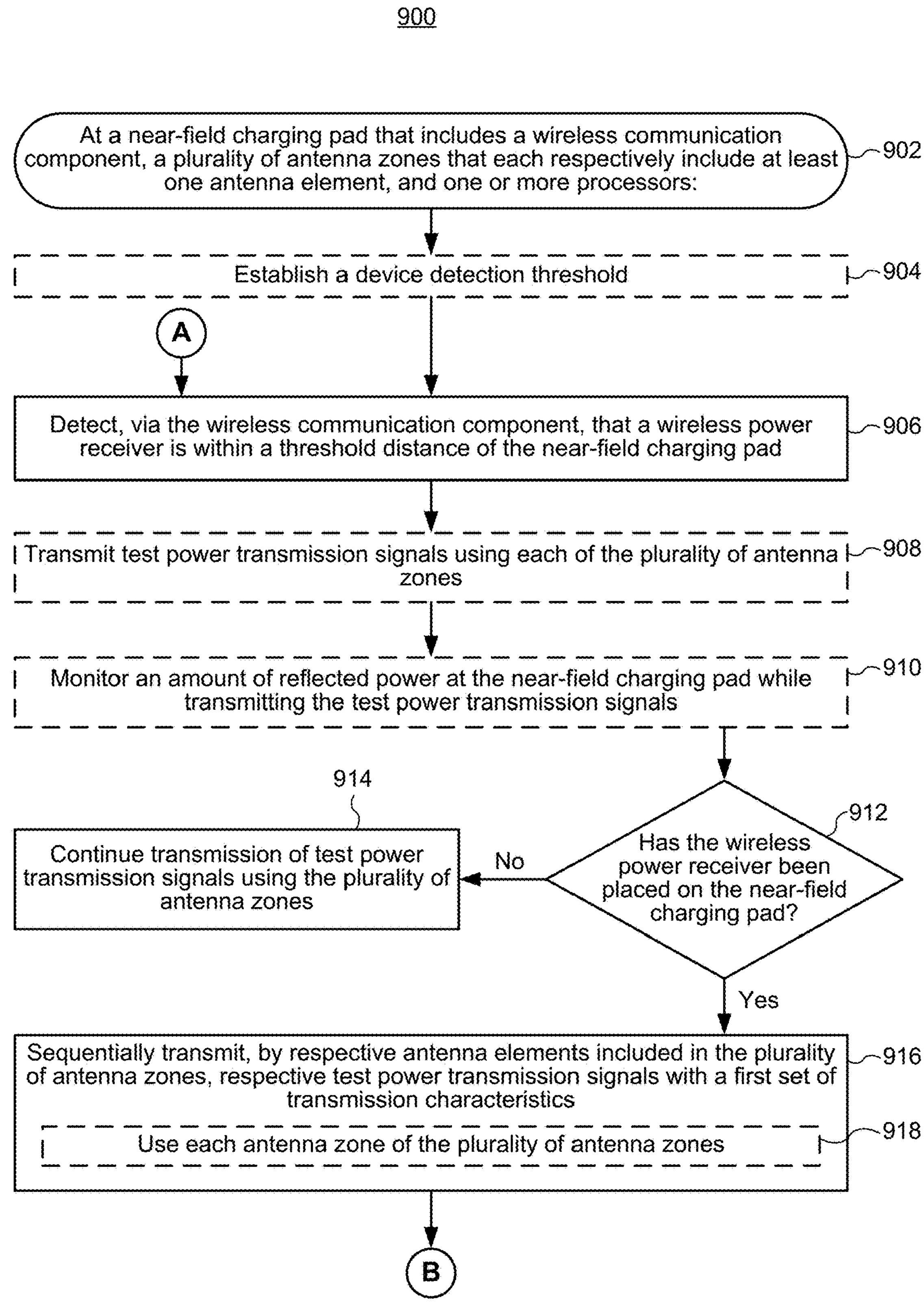

900
At a near-field charging pad that includes a wireless communication component, a plurality of antenna zones that each respectively include at least one antenna element, and one or more processors:
902
Establish a device detection threshold
904
A
Detect, via the wireless communication component, that a wireless power receiver is within a threshold distance of the near-field charging pad
906
Transmit test power transmission signals using each of the plurality of antenna zones
908
Monitor an amount of reflected power at the near-field charging pad while transmitting the test power transmission signals
910
914
Continue transmission of test power transmission signals using the plurality of antenna zones
No
Has the wireless power receiver been placed on the near-field charging pad?
912
Yes
Sequentially transmit, by respective antenna elements included in the plurality of antenna zones, respective test power transmission signals with a first set of transmission characteristics
916
Use each antenna zone of the plurality of antenna zones
918
B

Figure 9A

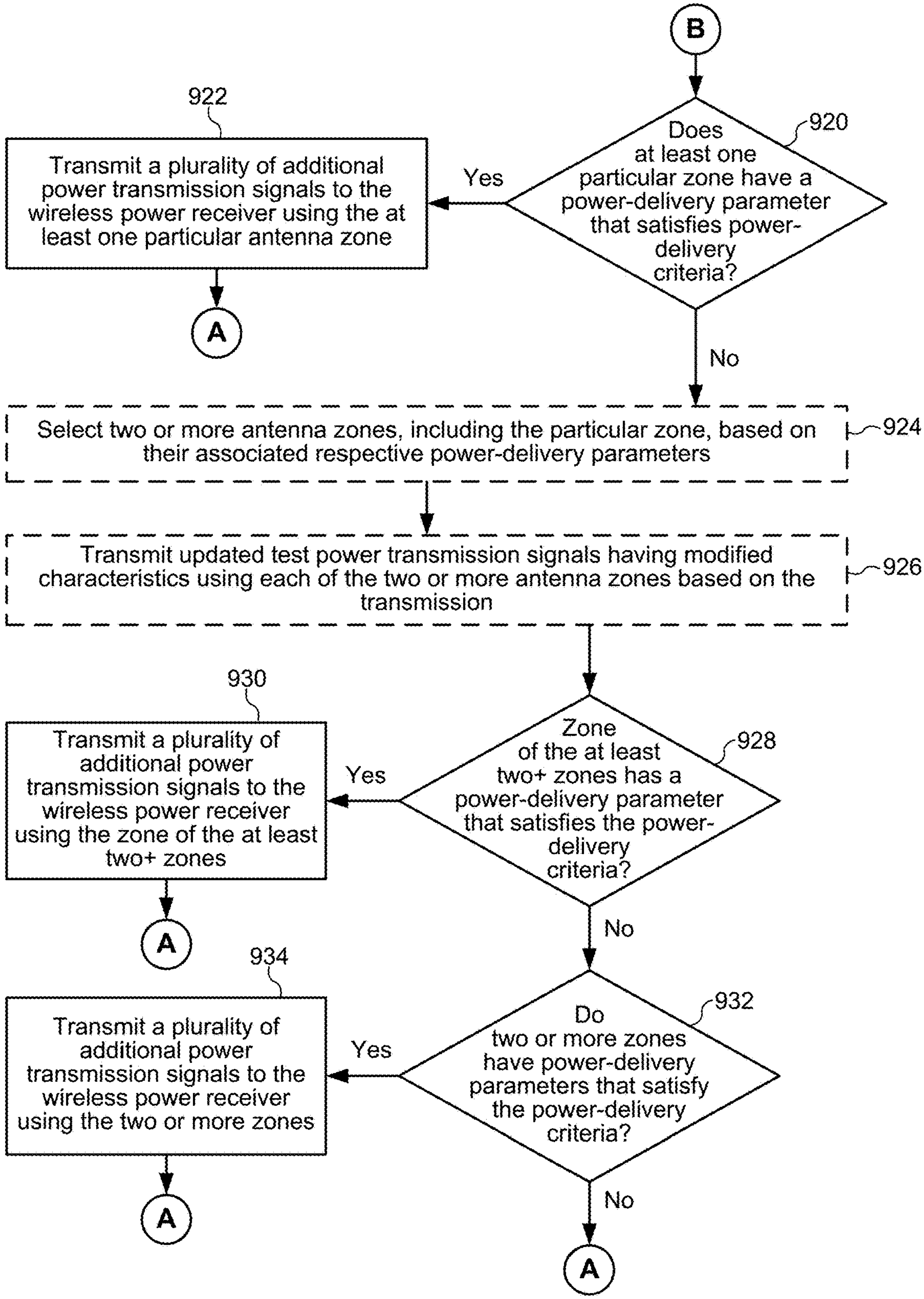

B
Does at least one particular zone have a power-delivery parameter that satisfies power-delivery criteria?
920
Yes
922
Transmit a plurality of additional power transmission signals to the wireless power receiver using the at least one particular antenna zone
A
No
Select two or more antenna zones, including the particular zone, based on their associated respective power-delivery parameters
924
Transmit updated test power transmission signals having modified characteristics using each of the two or more antenna zones based on the transmission
926
Zone of the at least two+ zones has a power-delivery parameter that satisfies the power-delivery criteria?
928
Yes
930
Transmit a plurality of additional power transmission signals to the wireless power receiver using the zone of the at least two+ zones
A
No
Do two or more zones have power-delivery parameters that satisfy the power-delivery criteria?
932
Yes
934
Transmit a plurality of additional power transmission signals to the wireless power receiver using the two or more zones
A
No
A

Figure 9B

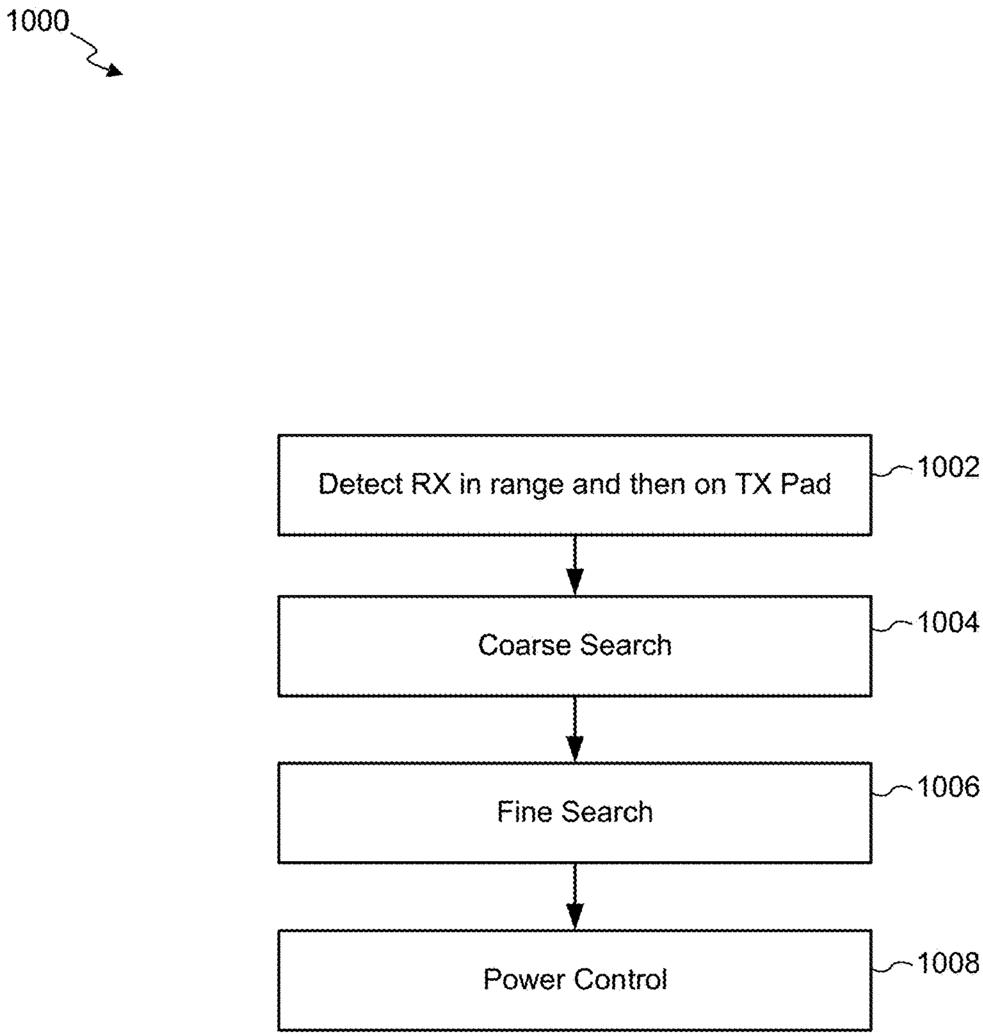

1000
Detect RX in range and then on TX Pad
1002
Coarse Search
1004
Fine Search
1006
Power Control
1008

Figure 10

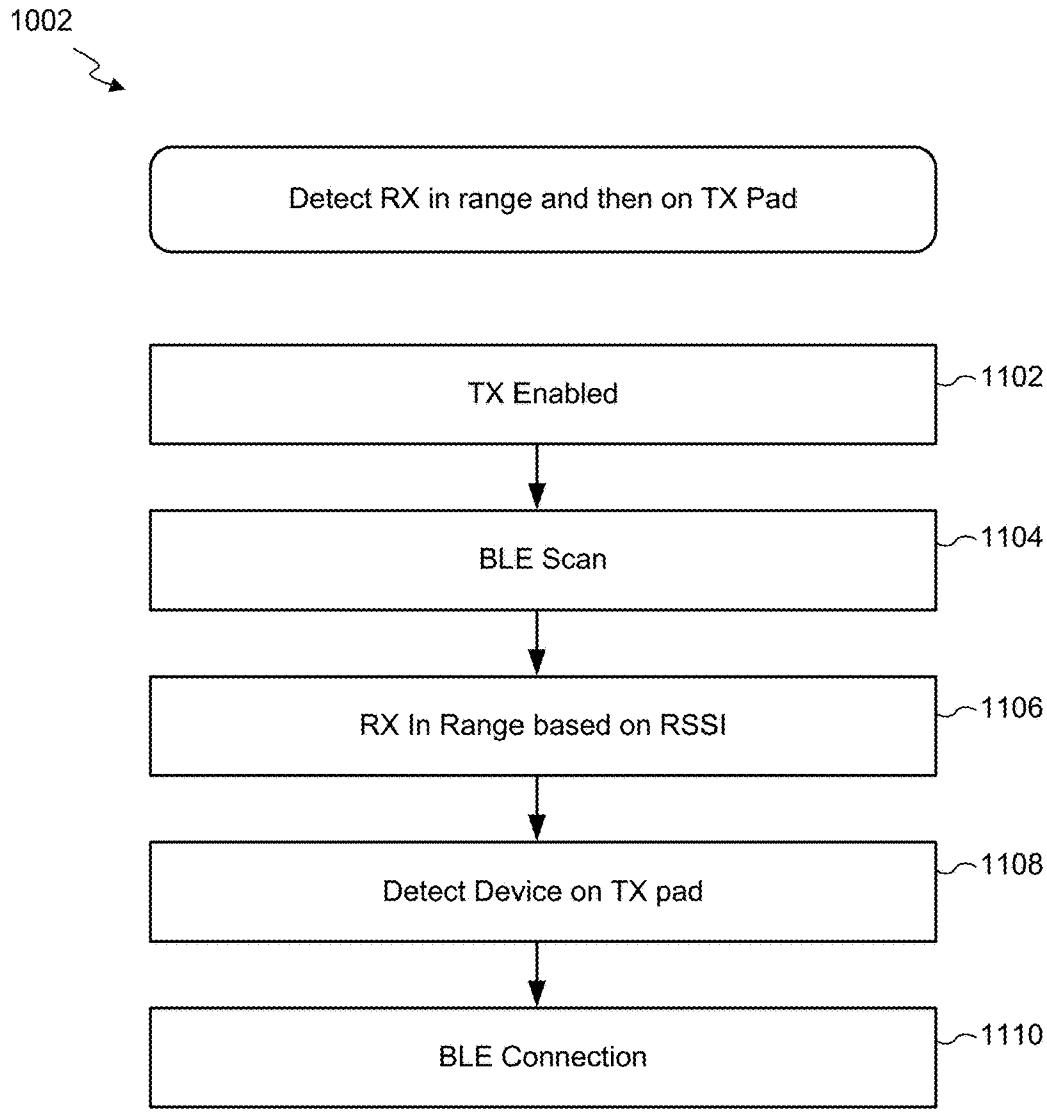

1002
Detect RX in range and then on TX Pad
TX Enabled
1102
BLE Scan
1104
RX In Range based on RSSI
1106
Detect Device on TX pad
1108
BLE Connection
1110

Figure 11A

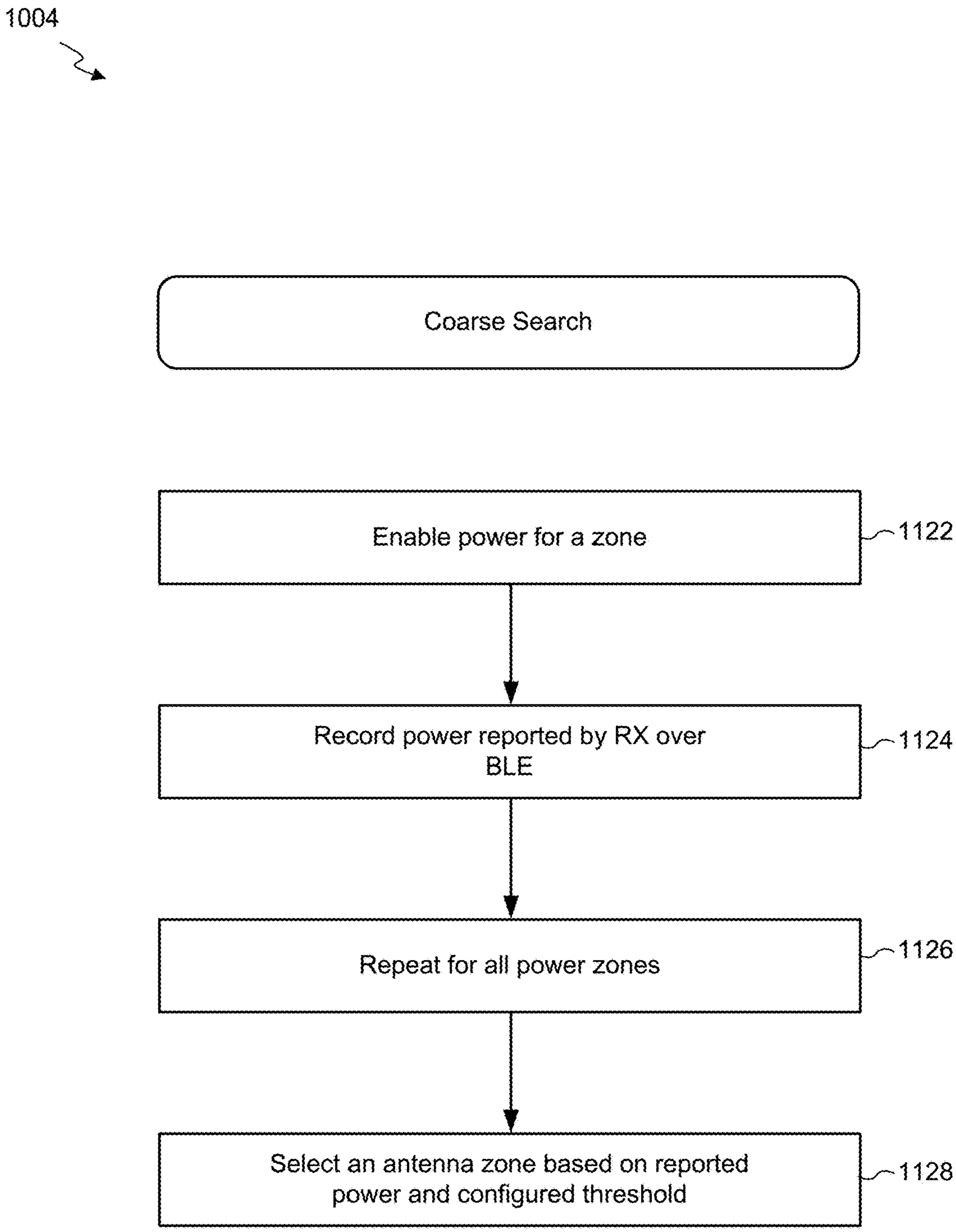

1004
Coarse Search
Enable power for a zone
1122
Record power reported by RX over BLE
1124
Repeat for all power zones
1126
Select an antenna zone based on reported power and configured threshold
1128

Figure 11B

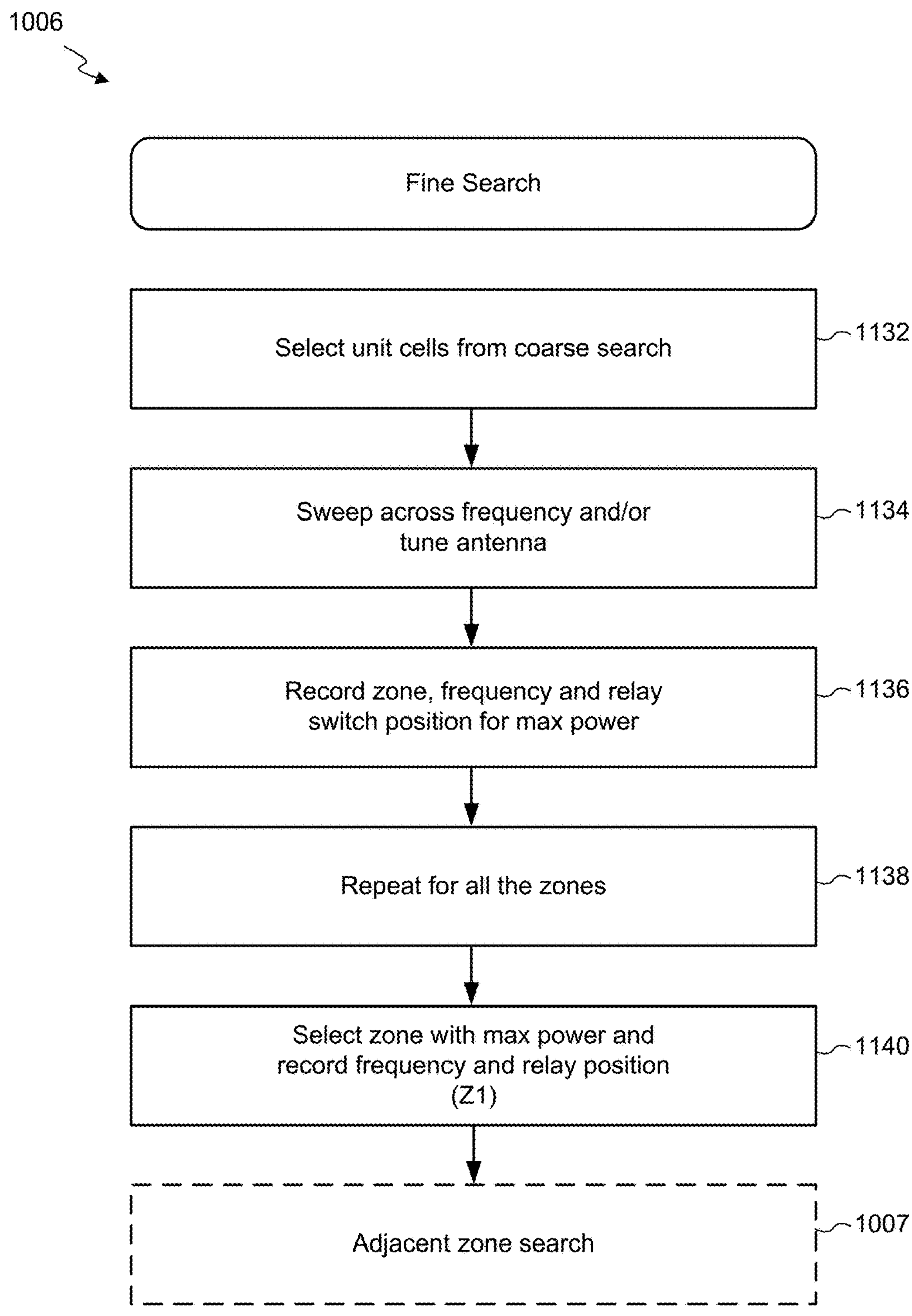

1006
Fine Search
Select unit cells from coarse search
1132
Sweep across frequency and/or tune antenna
1134
Record zone, frequency and relay switch position for max power
1136
Repeat for all the zones
1138
Select zone with max power and record frequency and relay position (Z1)
1140
Adjacent zone search
1007

Figure 11C

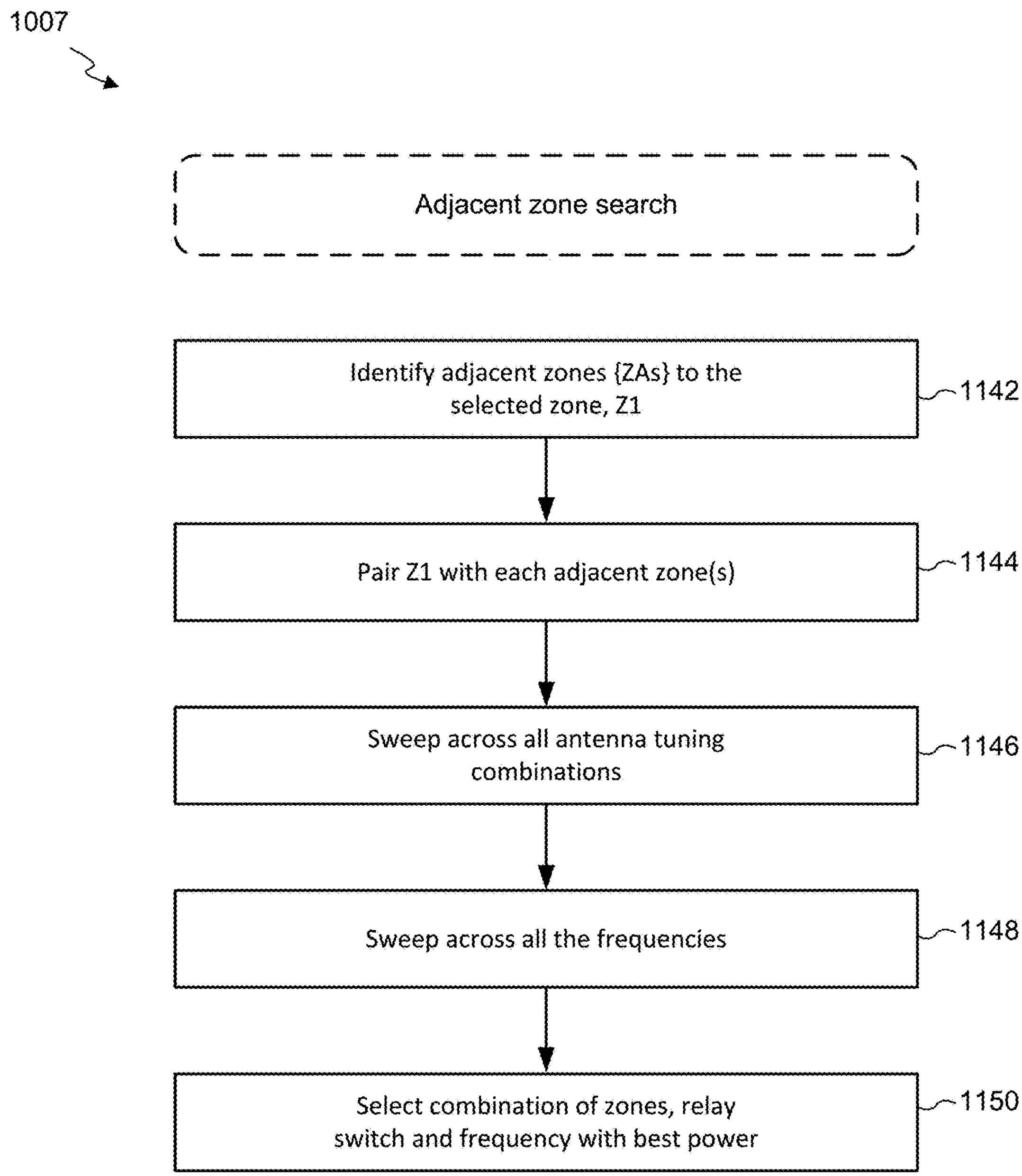

1007
Adjacent zone search
Identify adjacent zones {ZAs} to the selected zone, Z1
1142
Pair Z1 with each adjacent zone(s)
1144
Sweep across all antenna tuning combinations
1146
Sweep across all the frequencies
1148
Select combination of zones, relay switch and frequency with best power
1150

Figure 11D

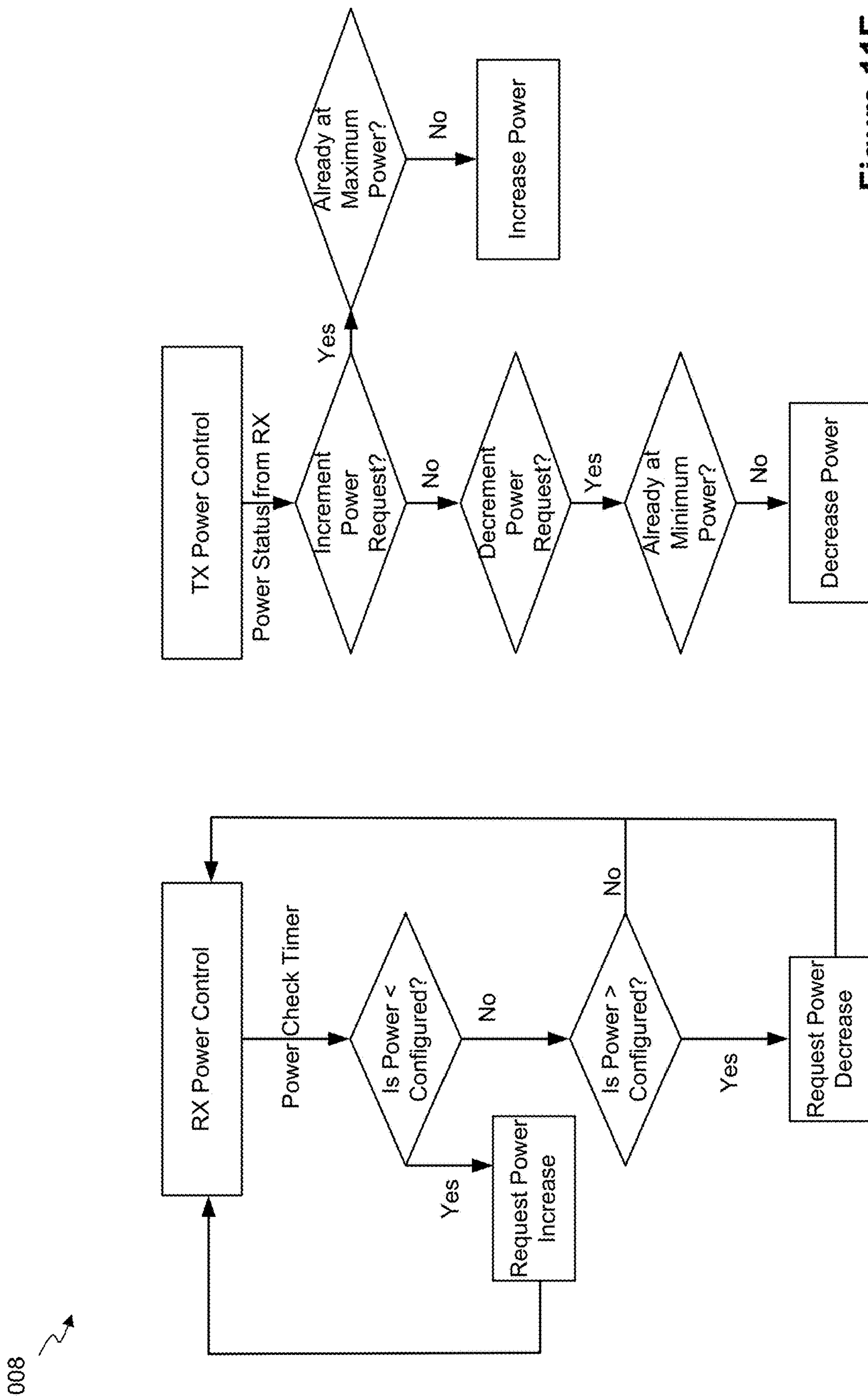

1008
RX Power Control
Power Check Timer
Is Power < Configured?
Yes
No
Request Power Increase
Is Power > Configured?
Yes
No
Request Power Decrease
TX Power Control
Power Status from RX
Increment Power Request?
Yes
No
Already at Maximum Power?
No
Increase Power
Decrement Power Request?
Yes
Already at Minimum Power?
No
Decrease Power

Figure 11E

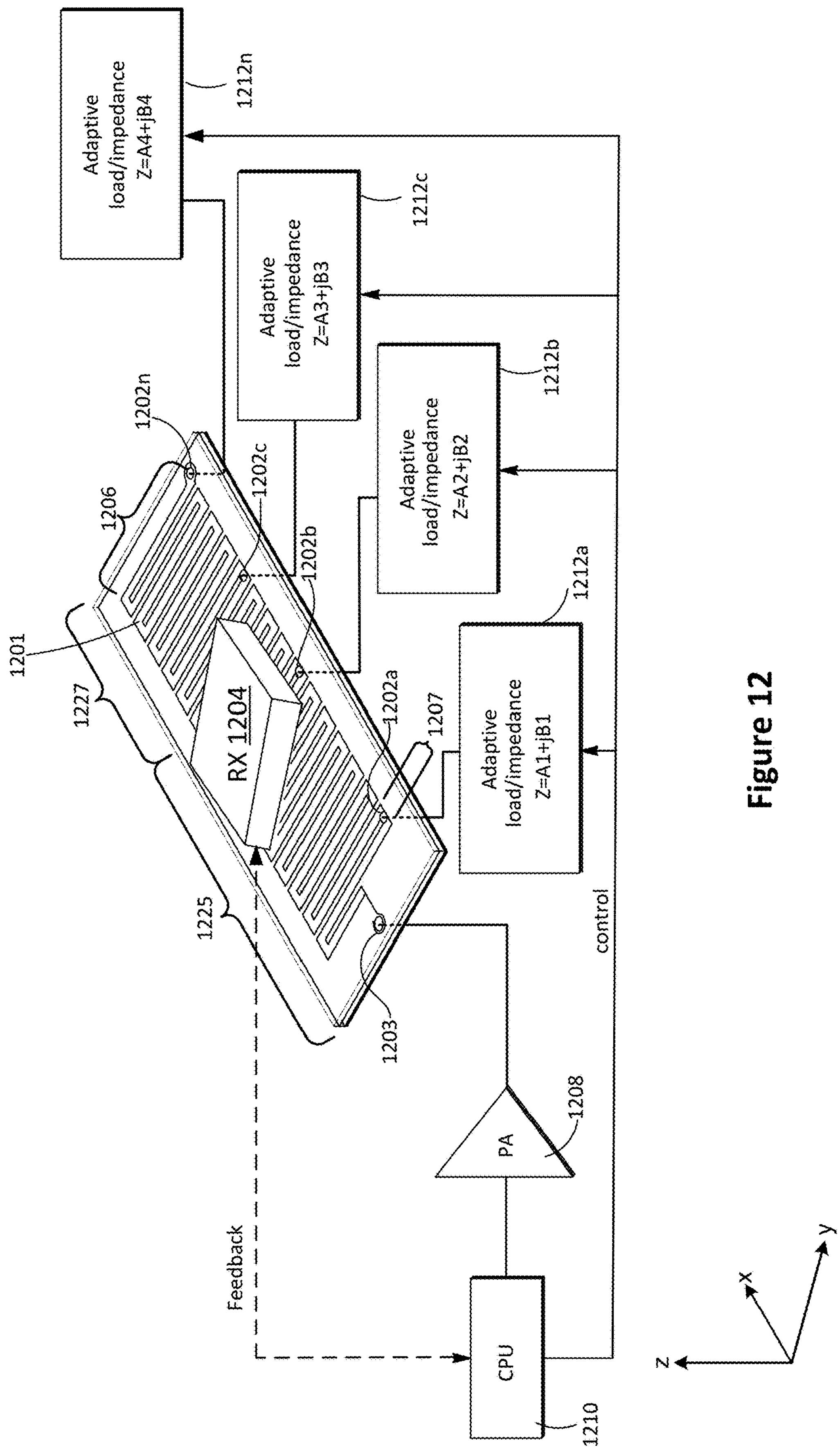

Adaptive load/impedance Z=A4+jB4
1212n
Adaptive load/impedance Z=A3+jB3
1212c
Adaptive load/impedance Z=A2+jB2
1212b
Adaptive load/impedance Z=A1+jB1
1212a
1202n
1202c
1202b
1202a
1206
1201
1227
1225
1207
1203
RX 1204
PA
1208
CPU
1210
Feedback
control
x
y
z

Figure 12

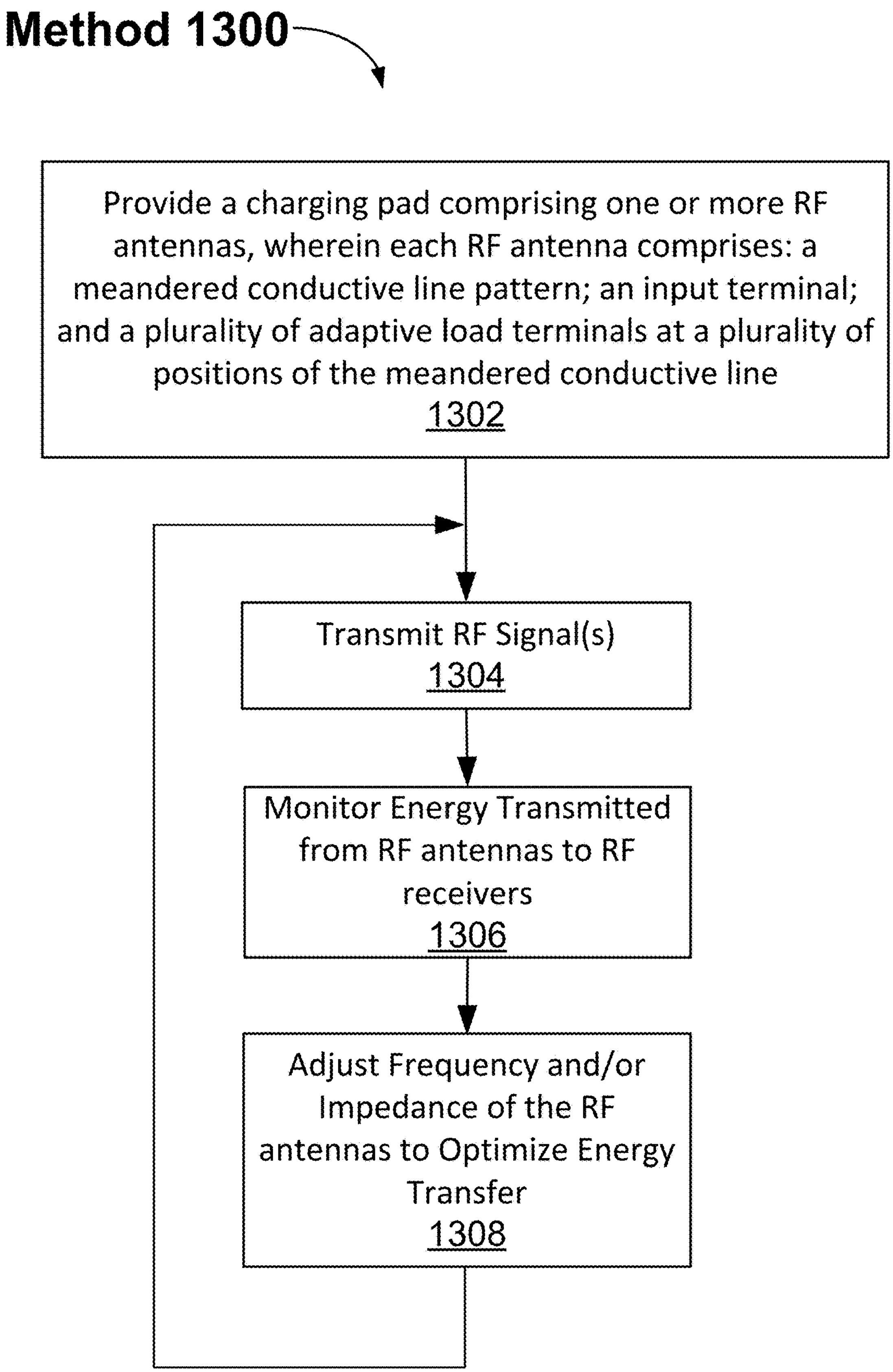

Method 1300
Provide a charging pad comprising one or more RF antennas, wherein each RF antenna comprises: a meandered conductive line pattern; an input terminal; and a plurality of adaptive load terminals at a plurality of positions of the meandered conductive line
1302
Transmit RF Signal(s)
1304
Monitor Energy Transmitted from RF antennas to RF receivers
1306
Adjust Frequency and/or Impedance of the RF antennas to Optimize Energy Transfer
1308

Figure 13

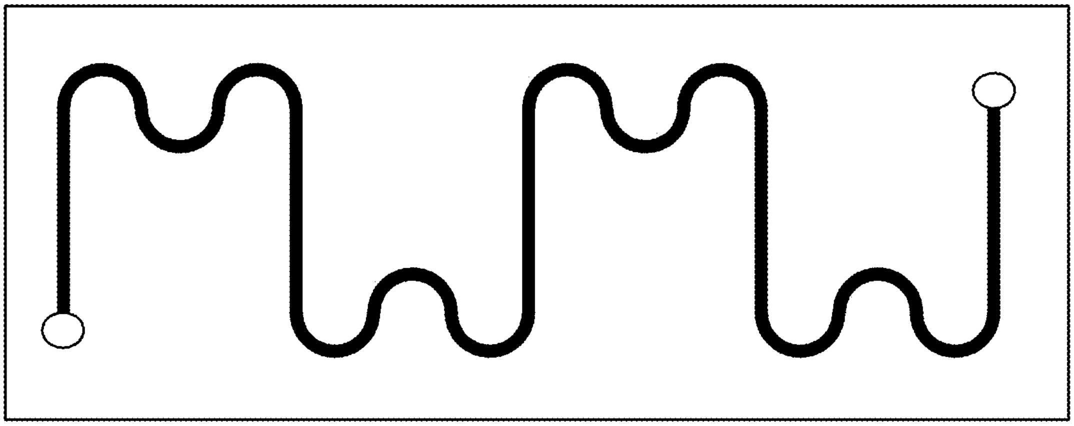


Figure 14A

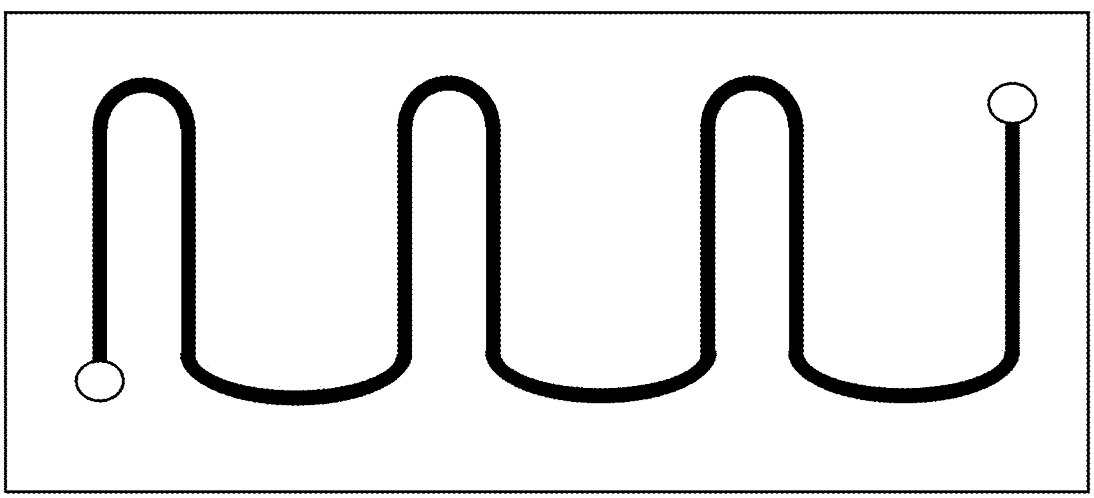


Figure 14B

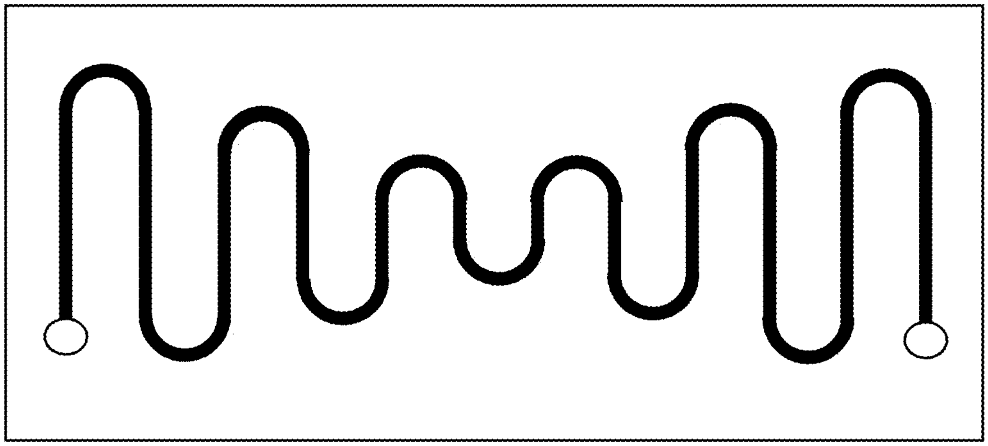


Figure 14C

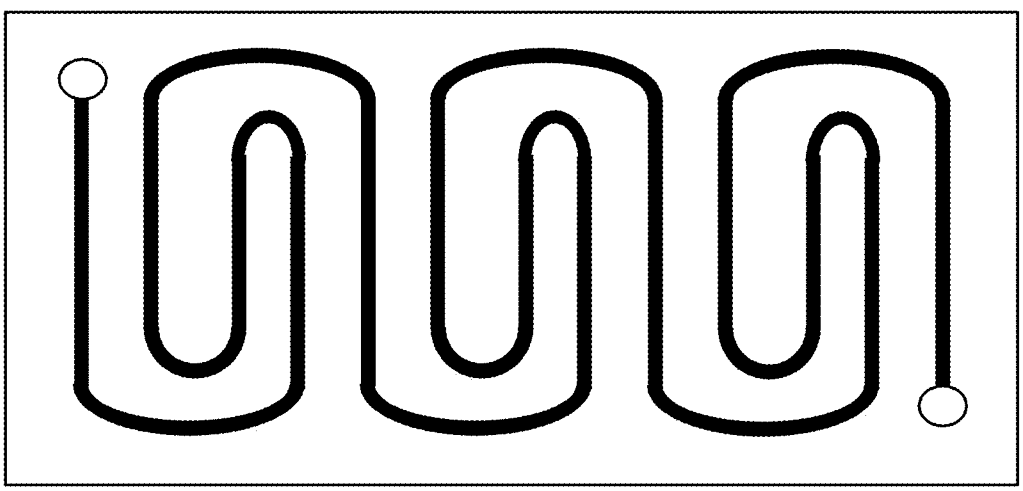


Figure 14D

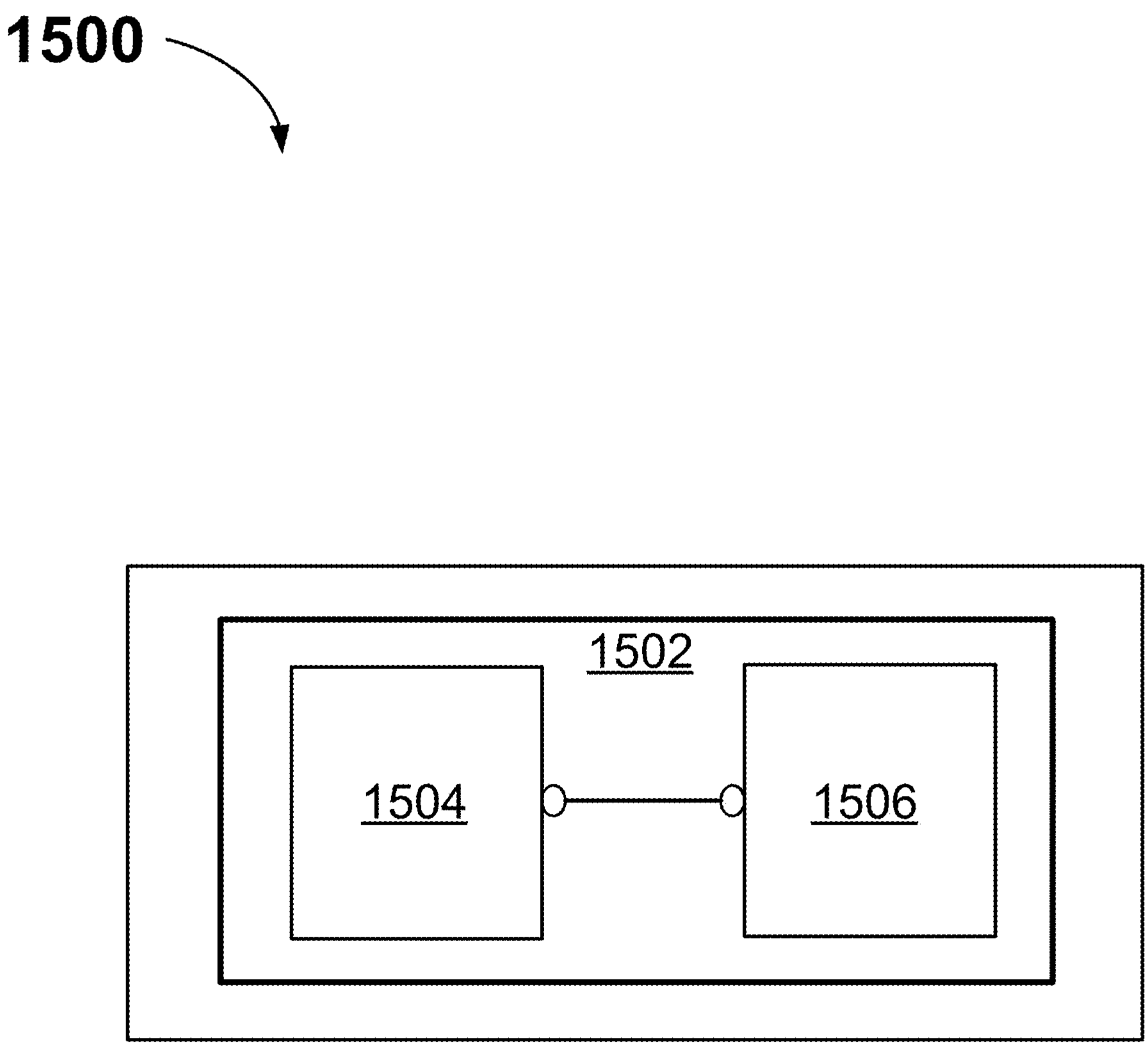


Figure 15

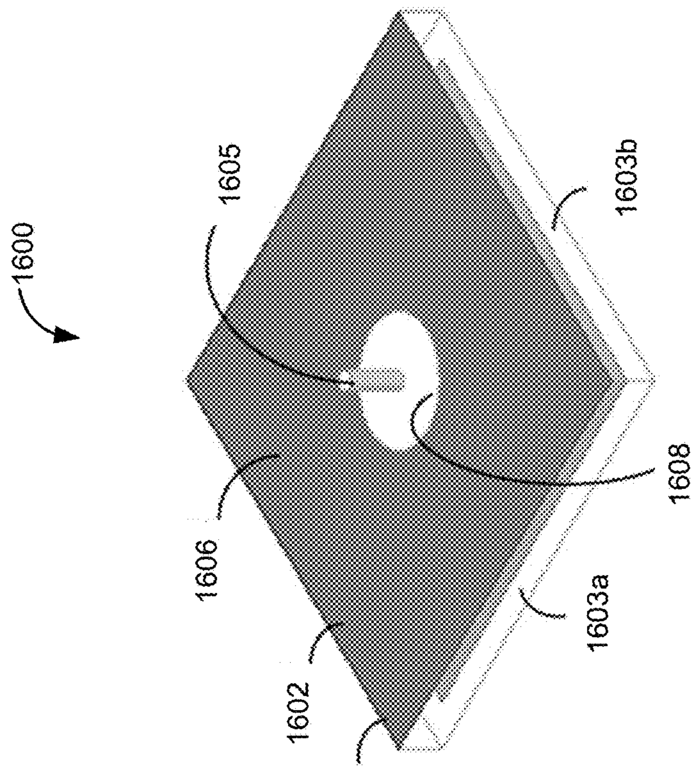


Figure 16B

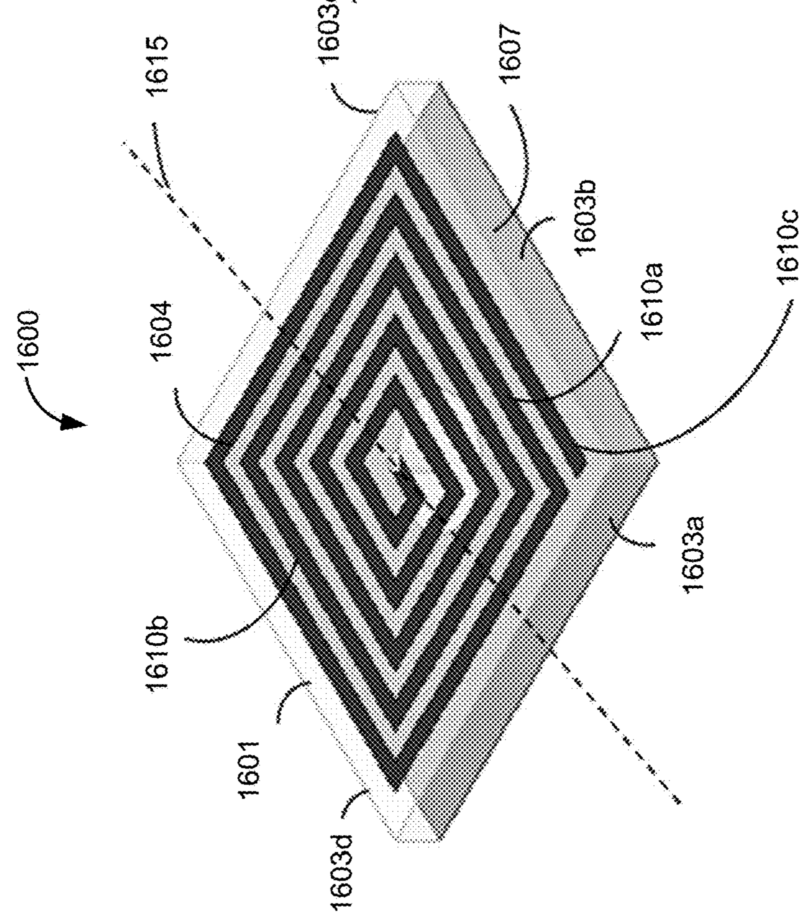


Figure 16A

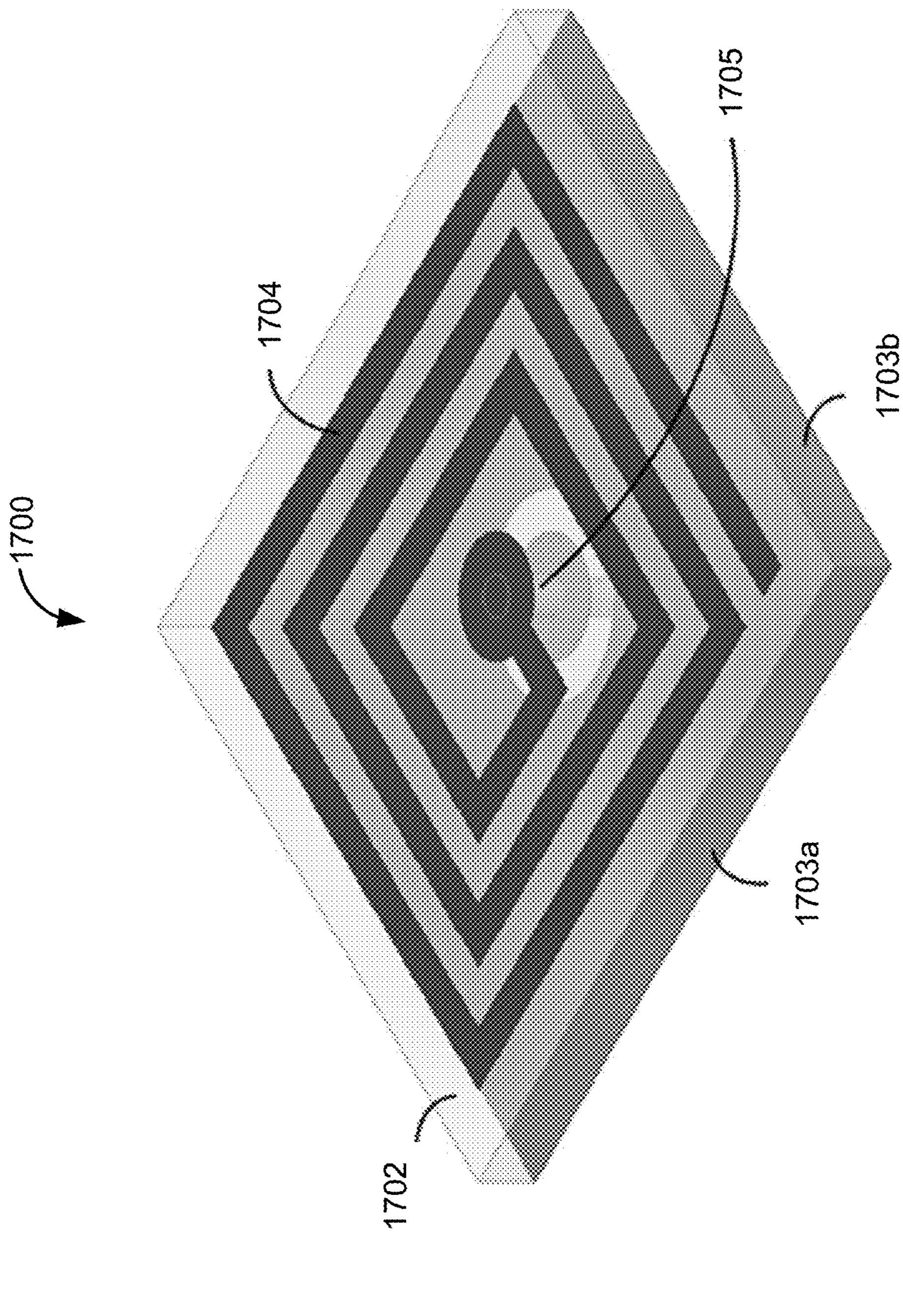


Figure 17A

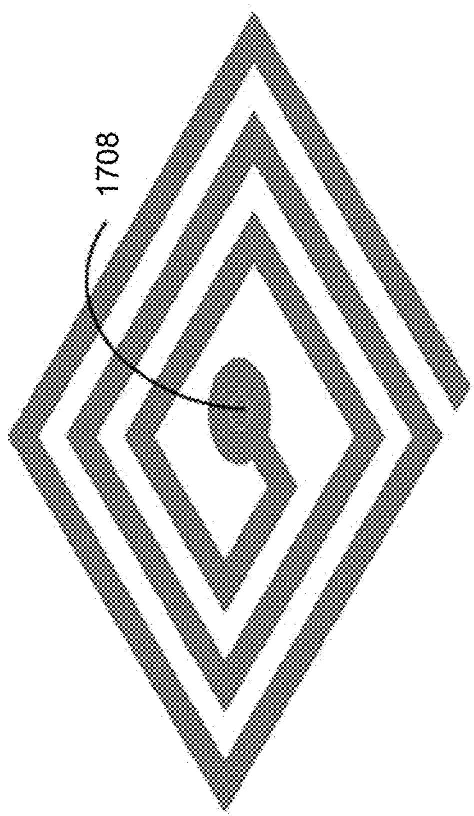


Figure 17C

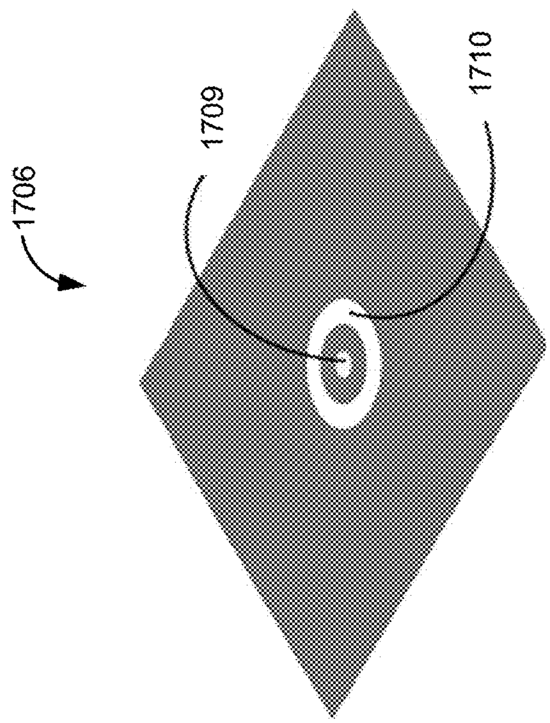


Figure 17D

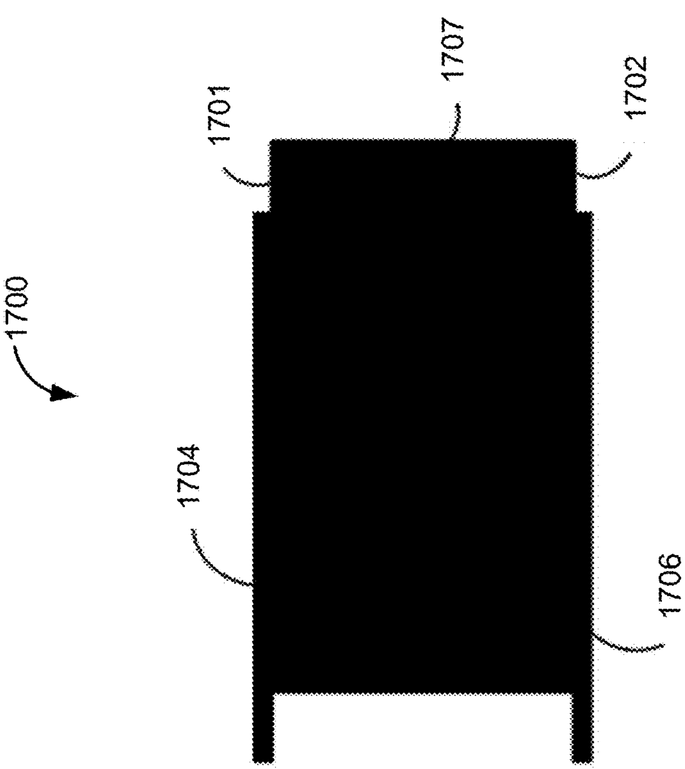


Figure 17B

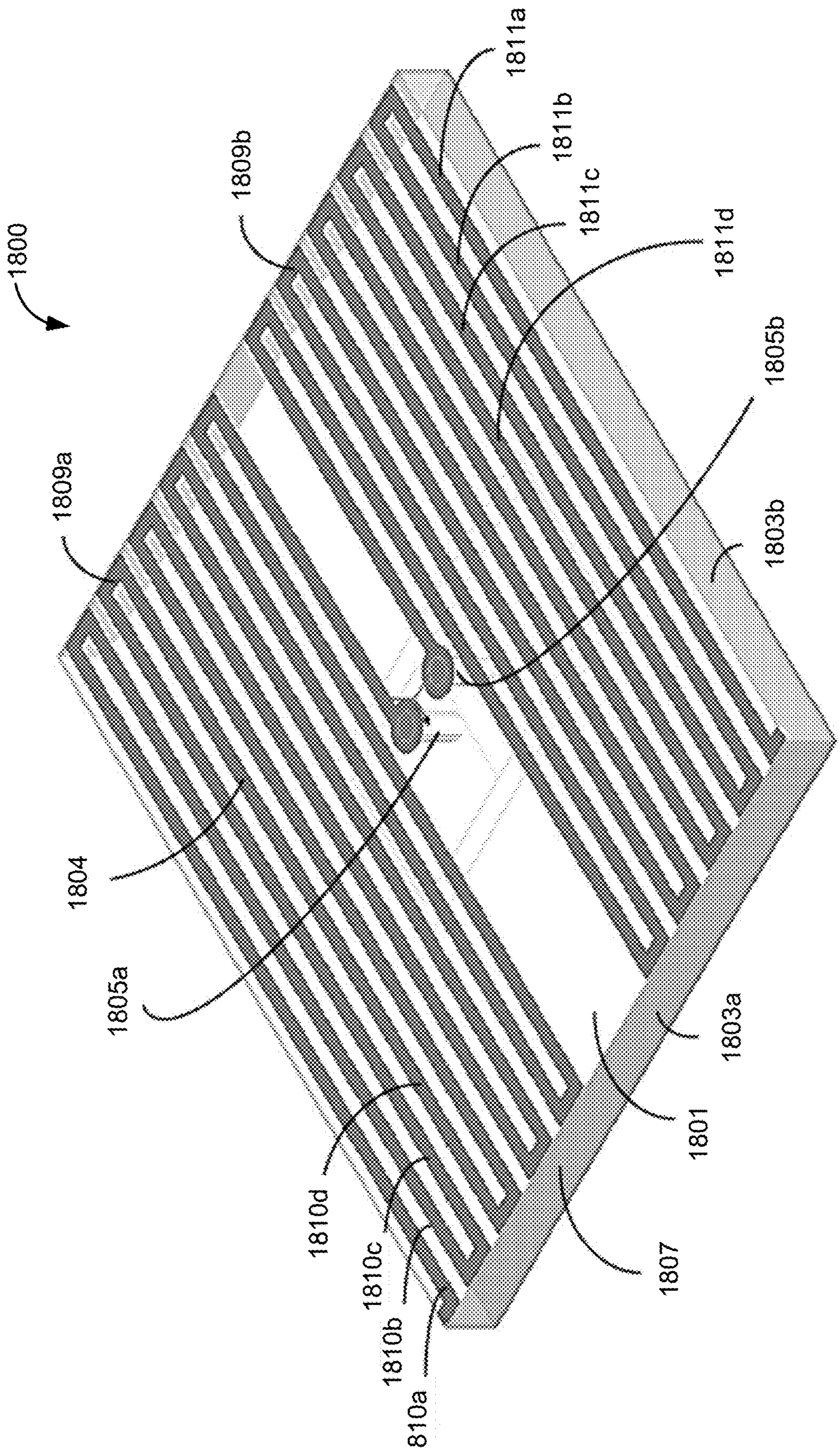

1800
1811a
1811b
1811c
1811d
1809b
1805b
1809a
1803b
1804
1805a
1803a
1801
1810d
1810c
1810b
1810a
1807

Figure 18

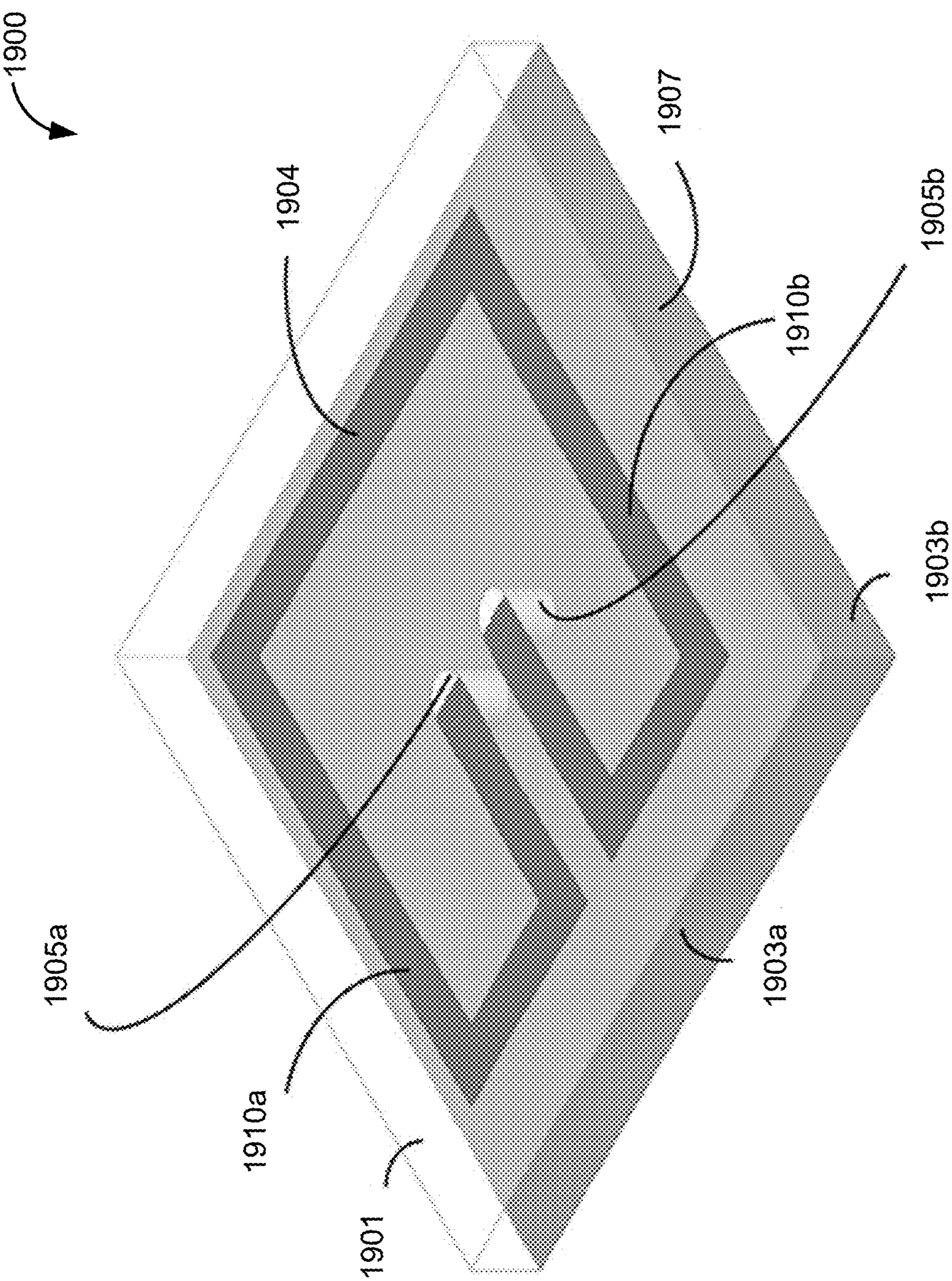
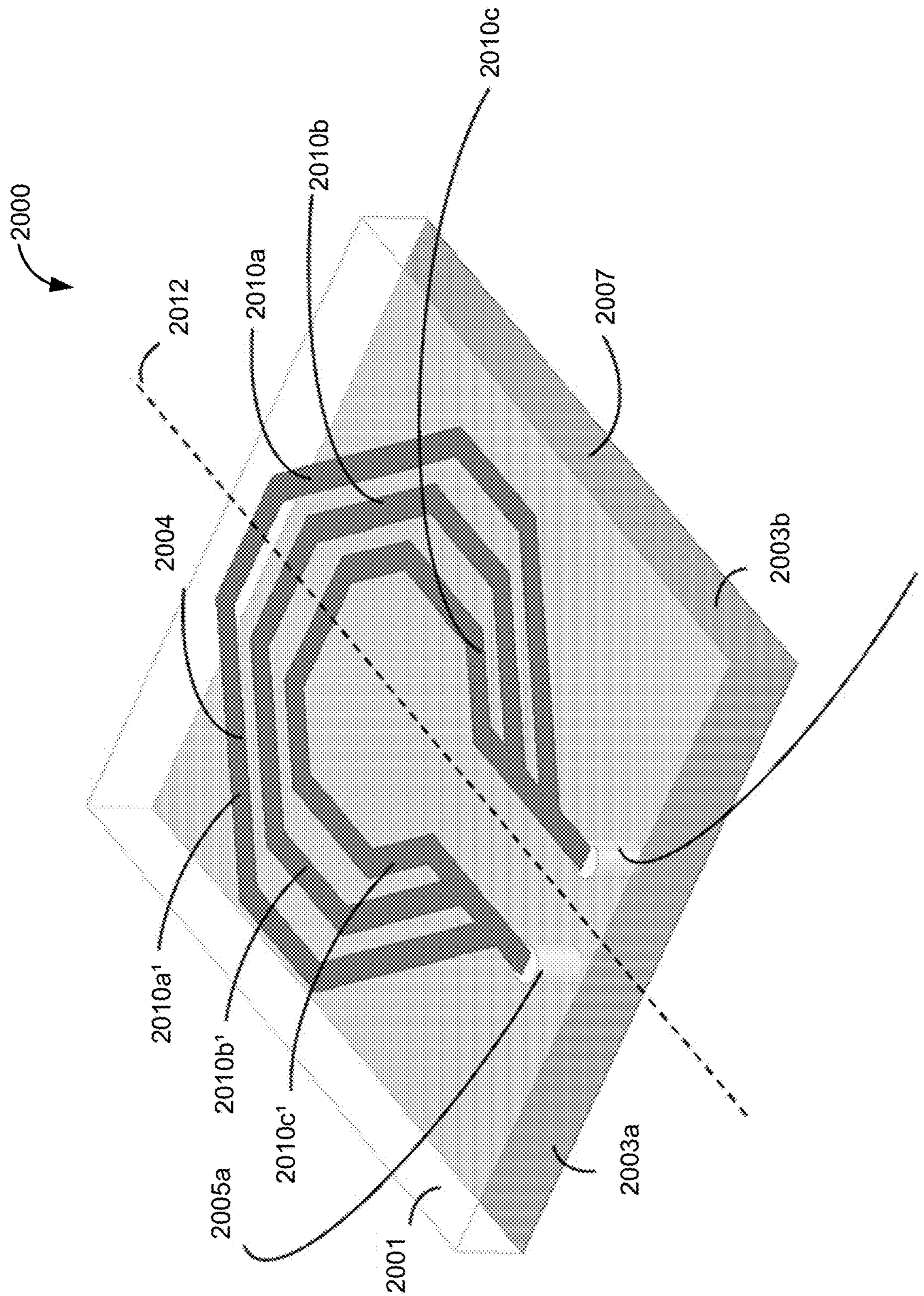


Figure 19



2000
2012
2010a
2010b
2010c
2007
2004
2003b
2005b
2010a¹
2010b¹
2010c¹
2005a
2001
2003a

Figure 20

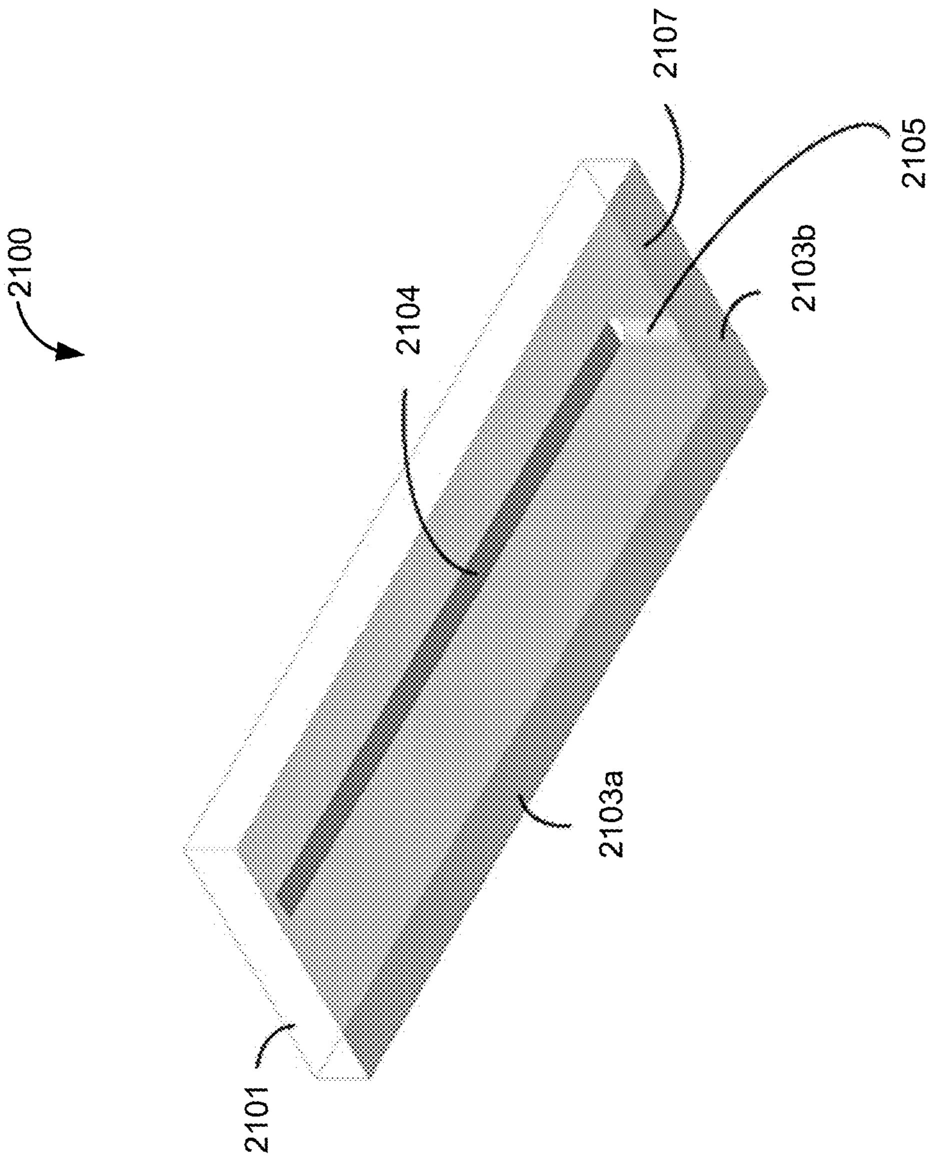


Figure 21

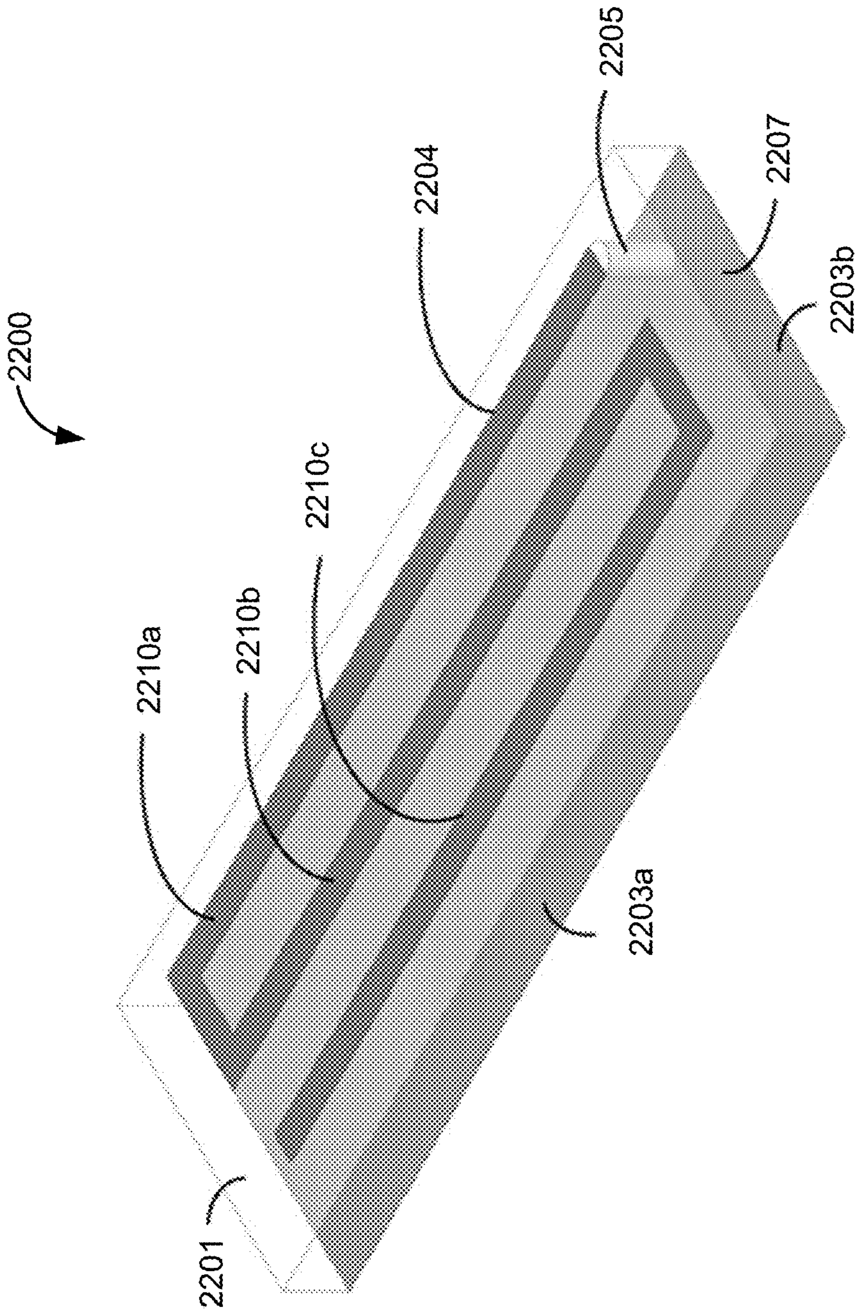


Figure 22

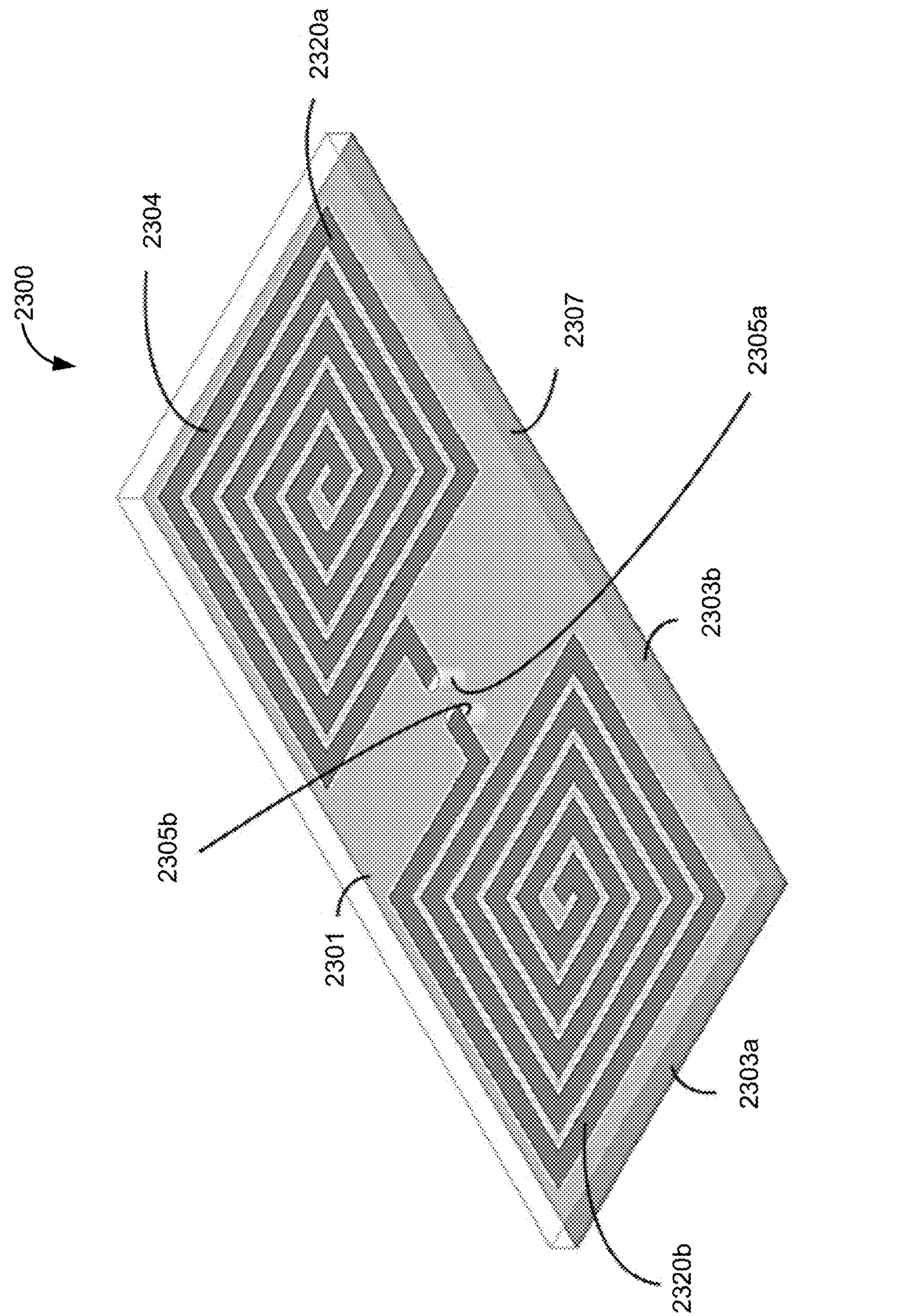


Figure 23

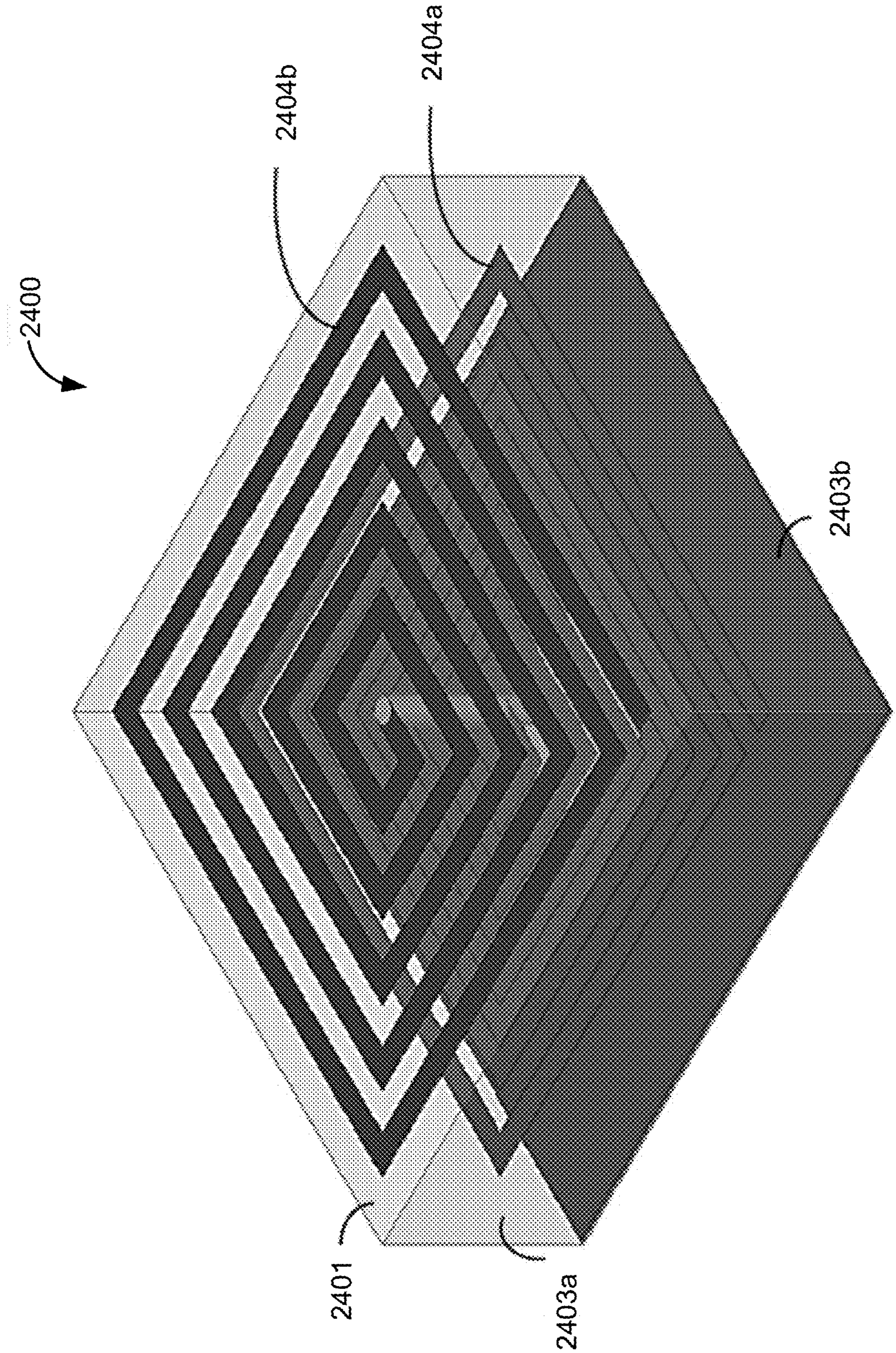


Figure 24A

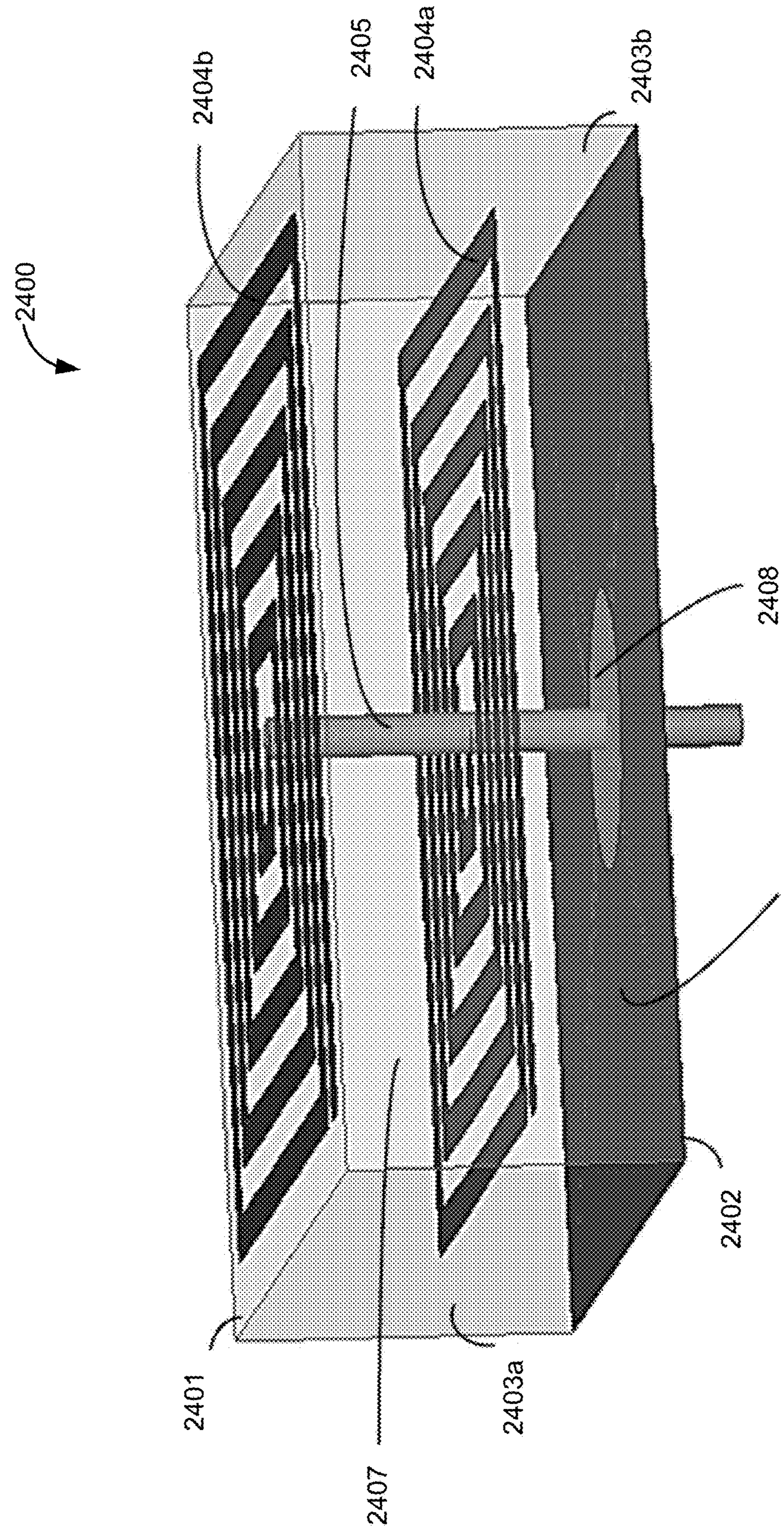


Figure 24B

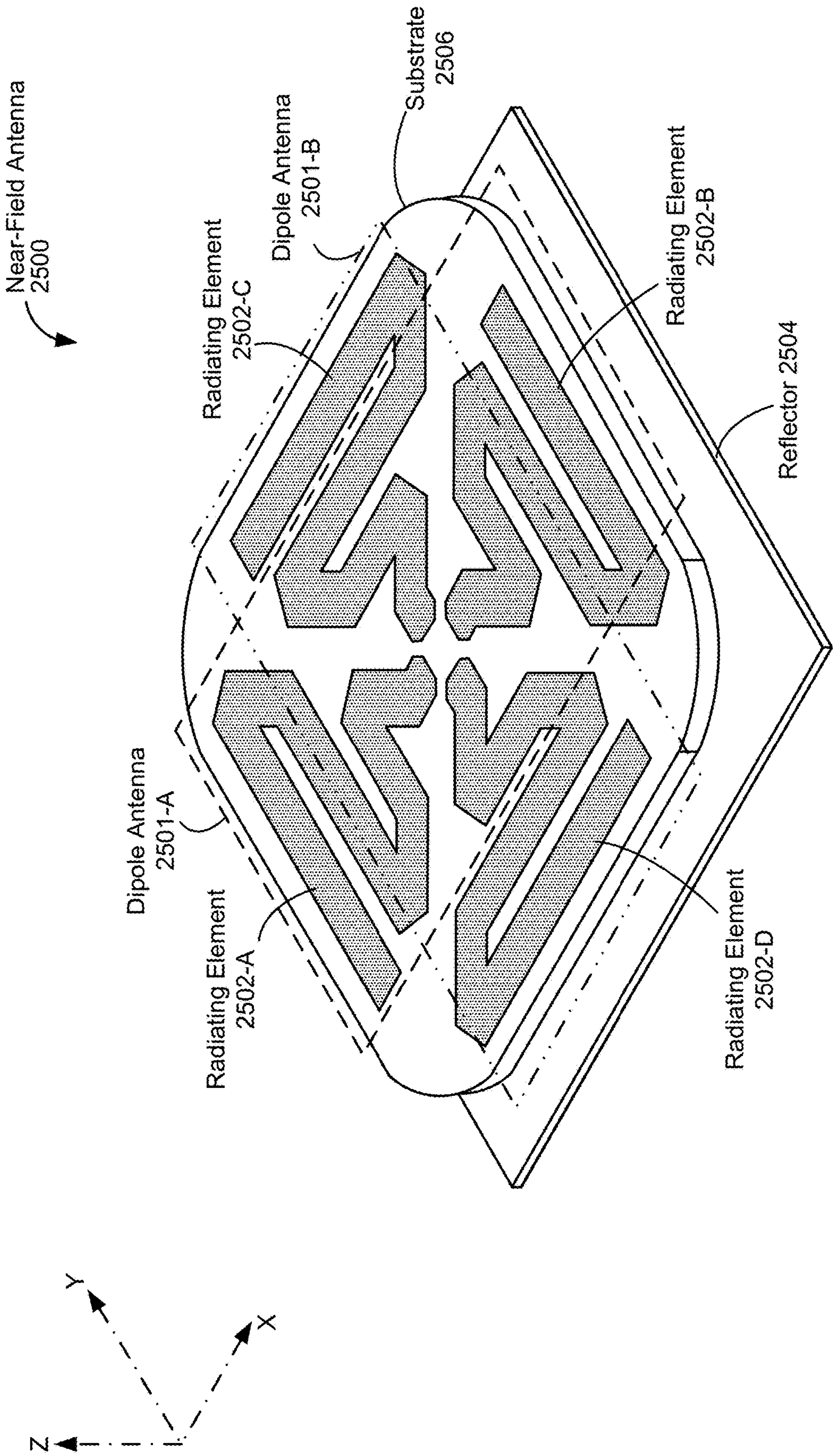

Near-Field Antenna
2500
Dipole Antenna
2501-B
Substrate
2506
Radiating Element
2502-C
Radiating Element
2502-B
Reflector 2504
Dipole Antenna
2501-A
Radiating Element
2502-A
Radiating Element
2502-D
Y
X
Z

Figure 25A

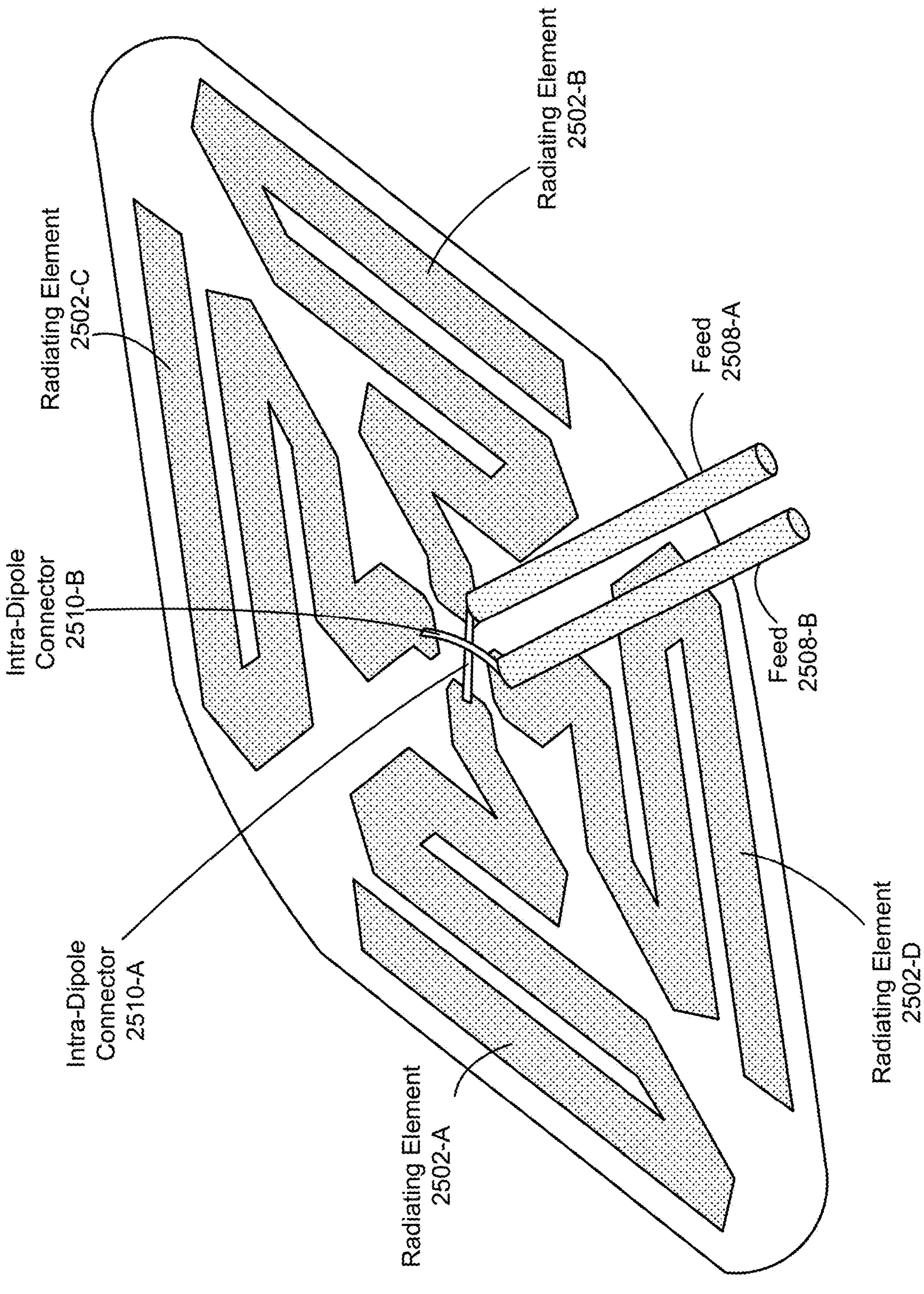

Radiating Element
2502-B
Radiating Element
2502-C
Feed
2508-A
Intra-Dipole
Connector
2510-B
Feed
2508-B
Intra-Dipole
Connector
2510-A
Radiating Element
2502-D
Radiating Element
2502-A

Figure 25B

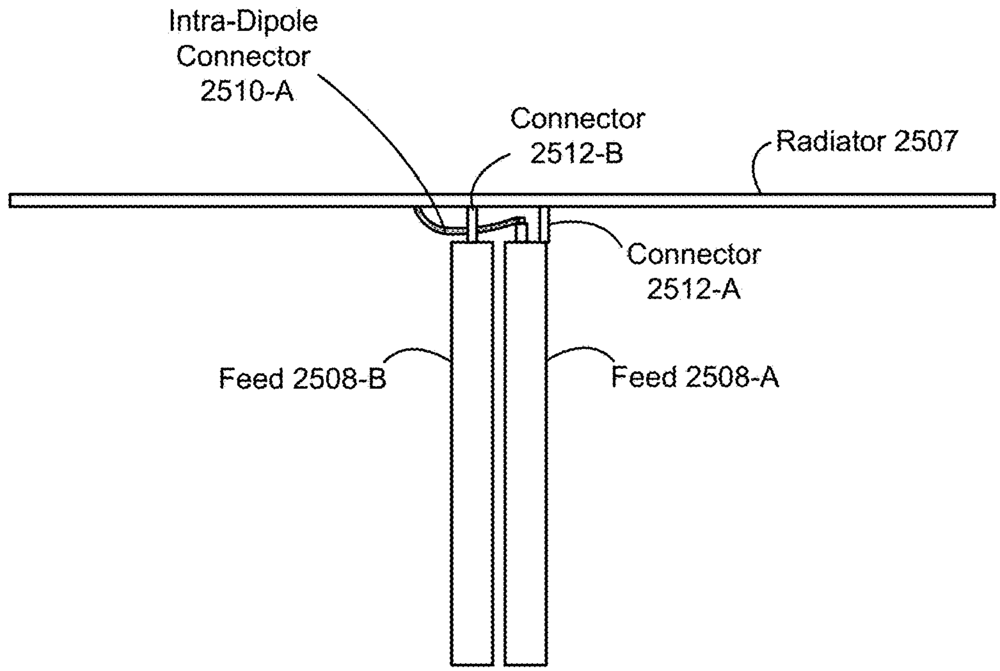


Figure 25C

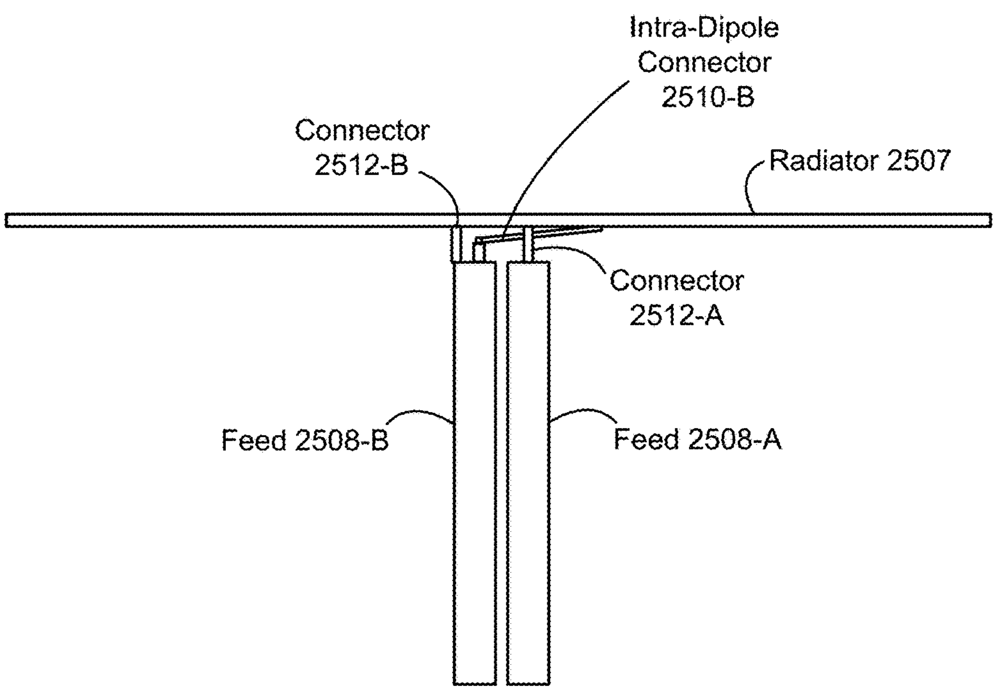
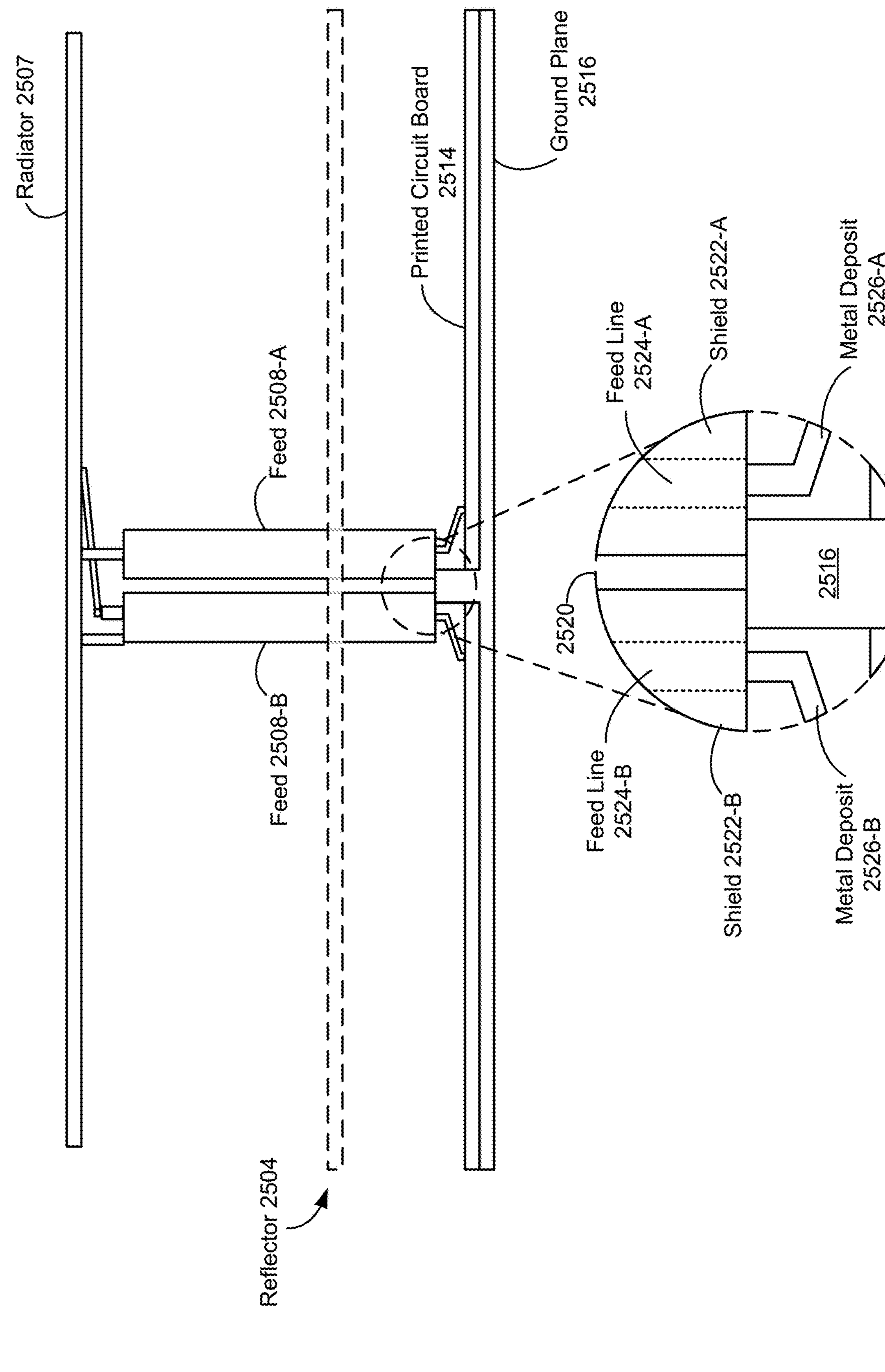


Figure 25D



Radiator 2507
Reflector 2504
Feed 2508-A
Feed 2508-B
Printed Circuit Board 2514
Ground Plane 2516
Feed Line 2524-A
Shield 2522-A
Metal Deposit 2526-A
2520
2516
Feed Line 2524-B
Shield 2522-B
Metal Deposit 2526-B

Figure 25E

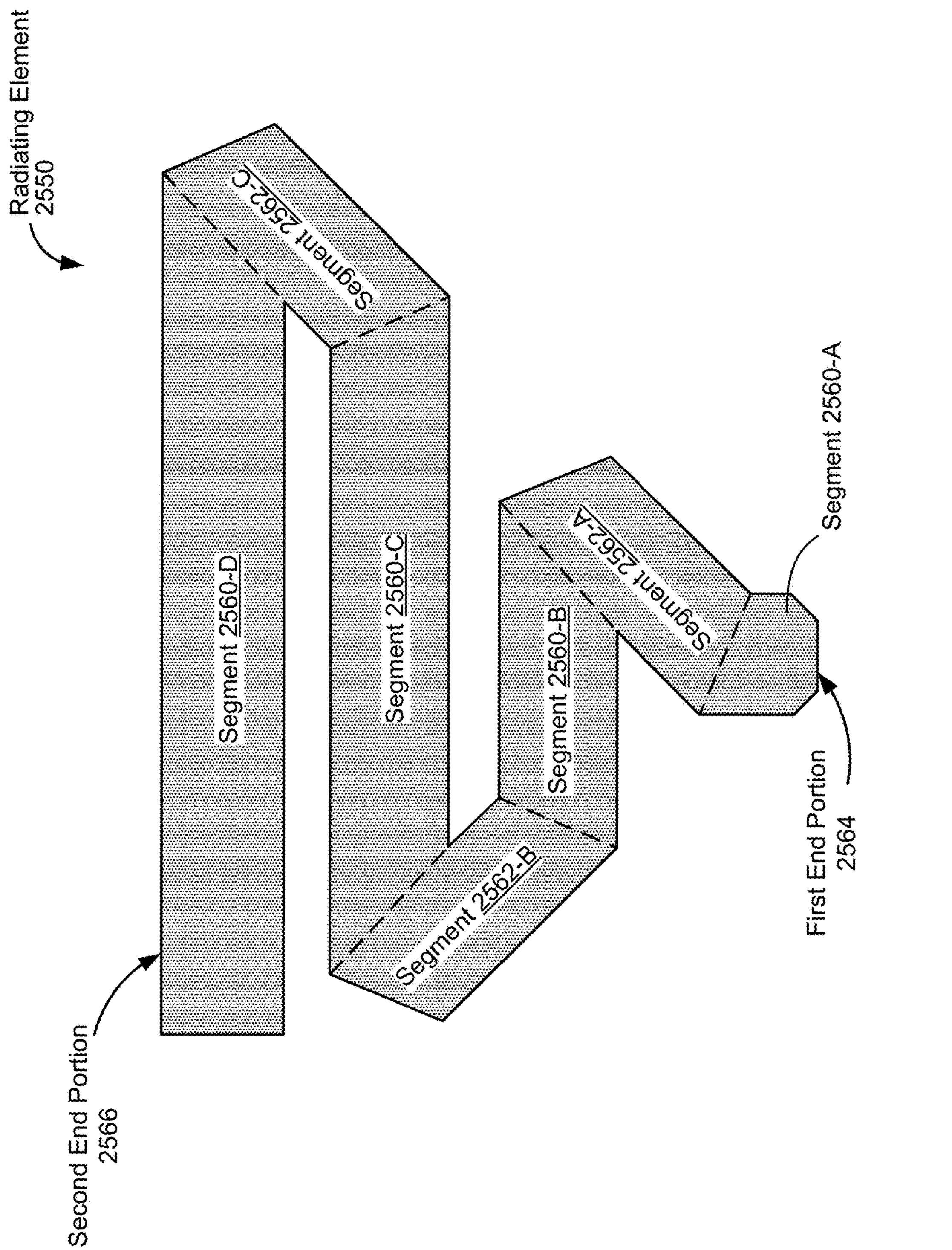

Radiating Element
2550
Segment 2562-C
Segment 2560-D
Segment 2560-C
Segment 2560-B
Segment 2562-A
Segment 2560-A
Segment 2562-B
First End Portion
2564
Second End Portion
2566

Figure 25F

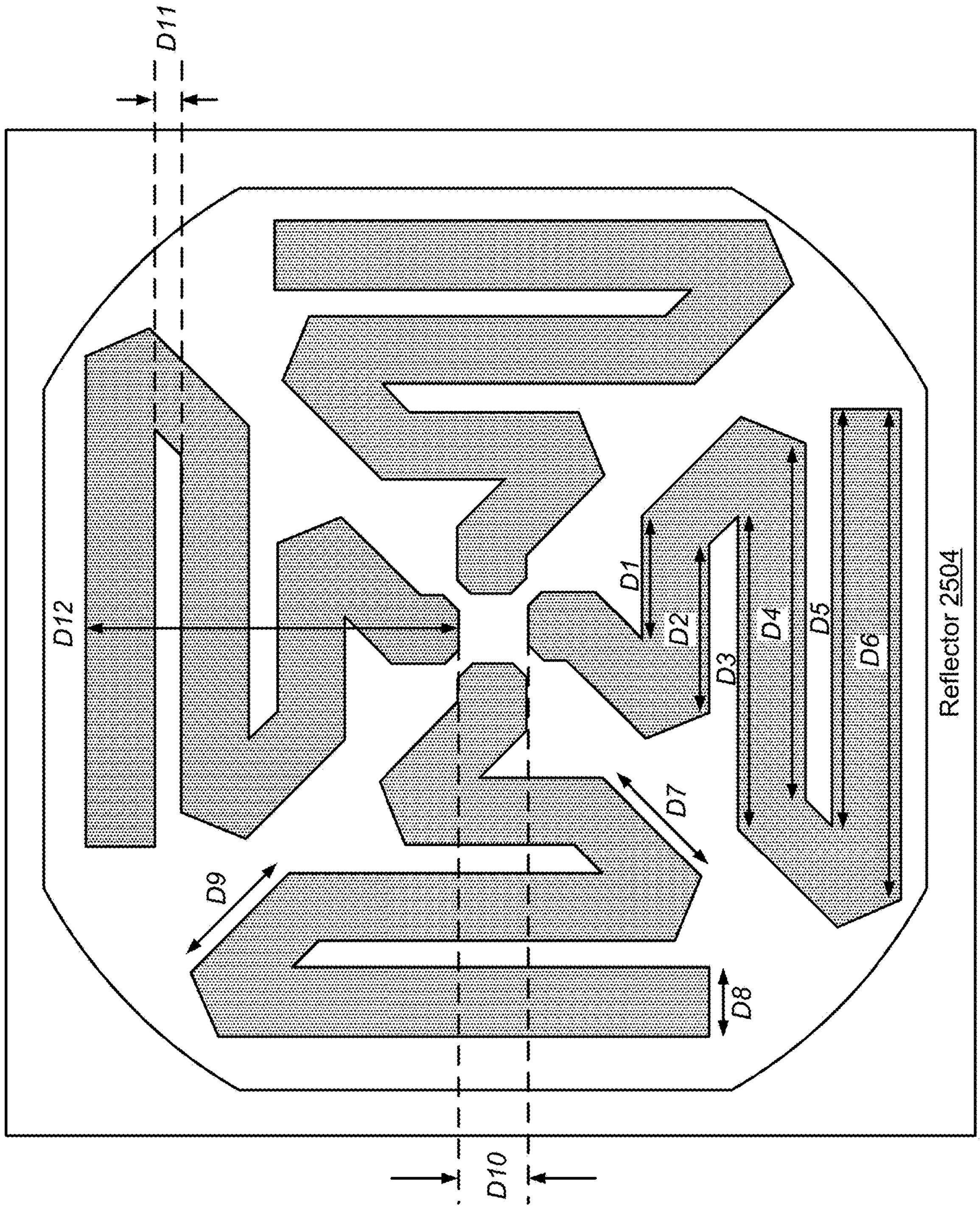


Figure 25G

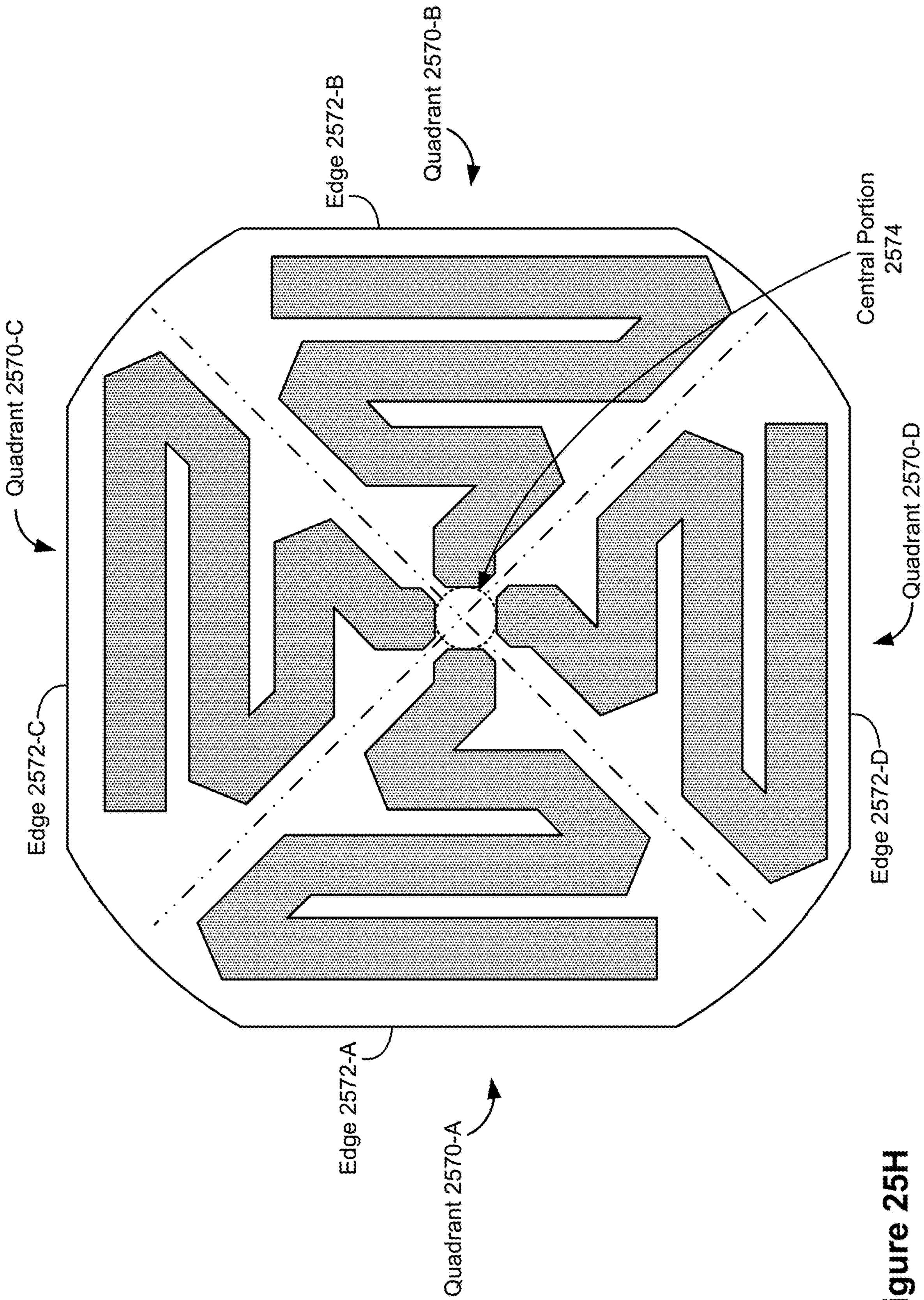

Quadrant 2570-B
Edge 2572-B
Central Portion 2574
Quadrant 2570-C
Quadrant 2570-D
Edge 2572-C
Edge 2572-D
Edge 2572-A
Quadrant 2570-A

Figure 25H

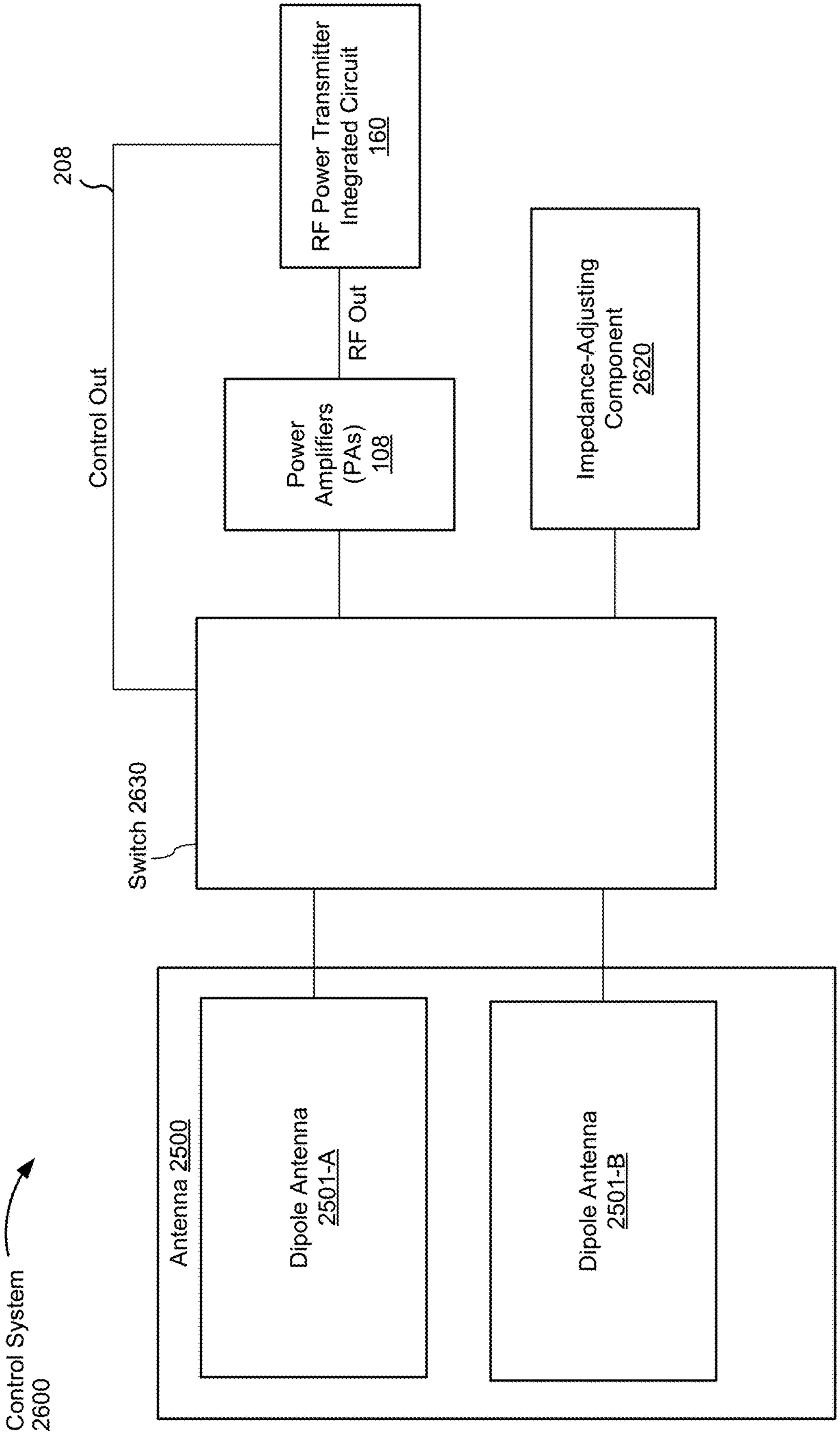

208
Control Out
RF Power Transmitter Integrated Circuit 160
RF Out
Power Amplifiers (PAs) 108
Impedance-Adjusting Component 2620
Switch 2630
Antenna 2500
Dipole Antenna 2501-A
Dipole Antenna 2501-B
Control System 2600

FIGURE 26

Radiation Pattern
2700

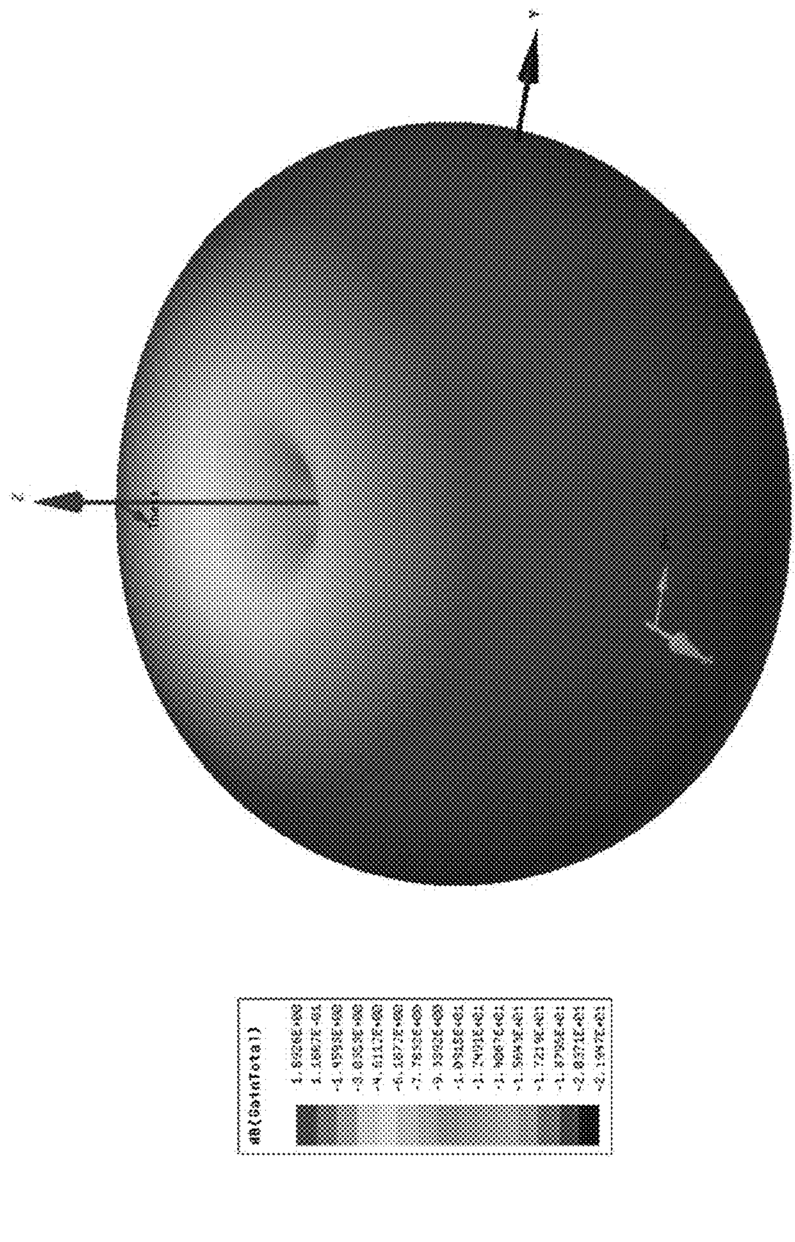


Figure 27

Radiation Pattern
2800

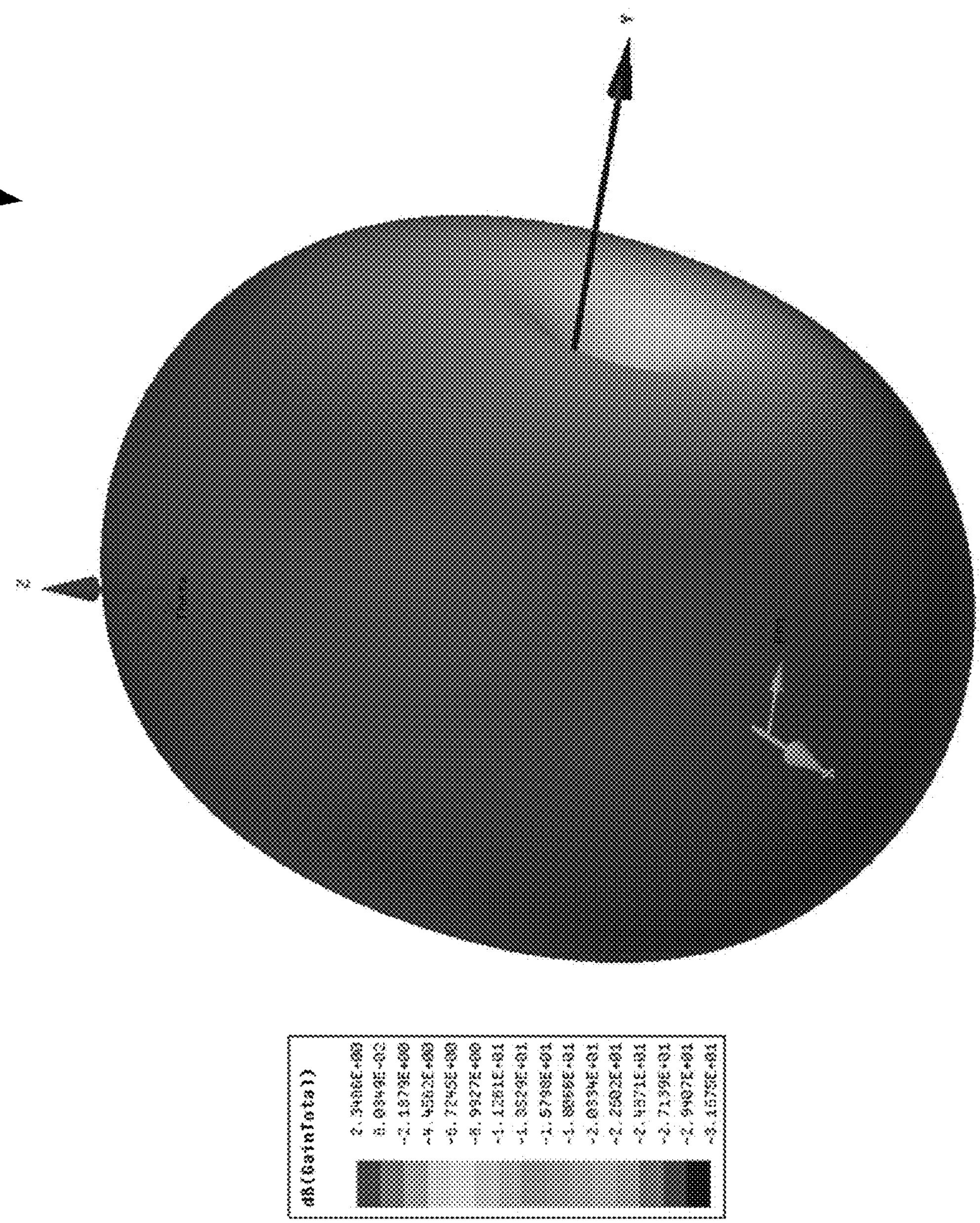


Figure 28A

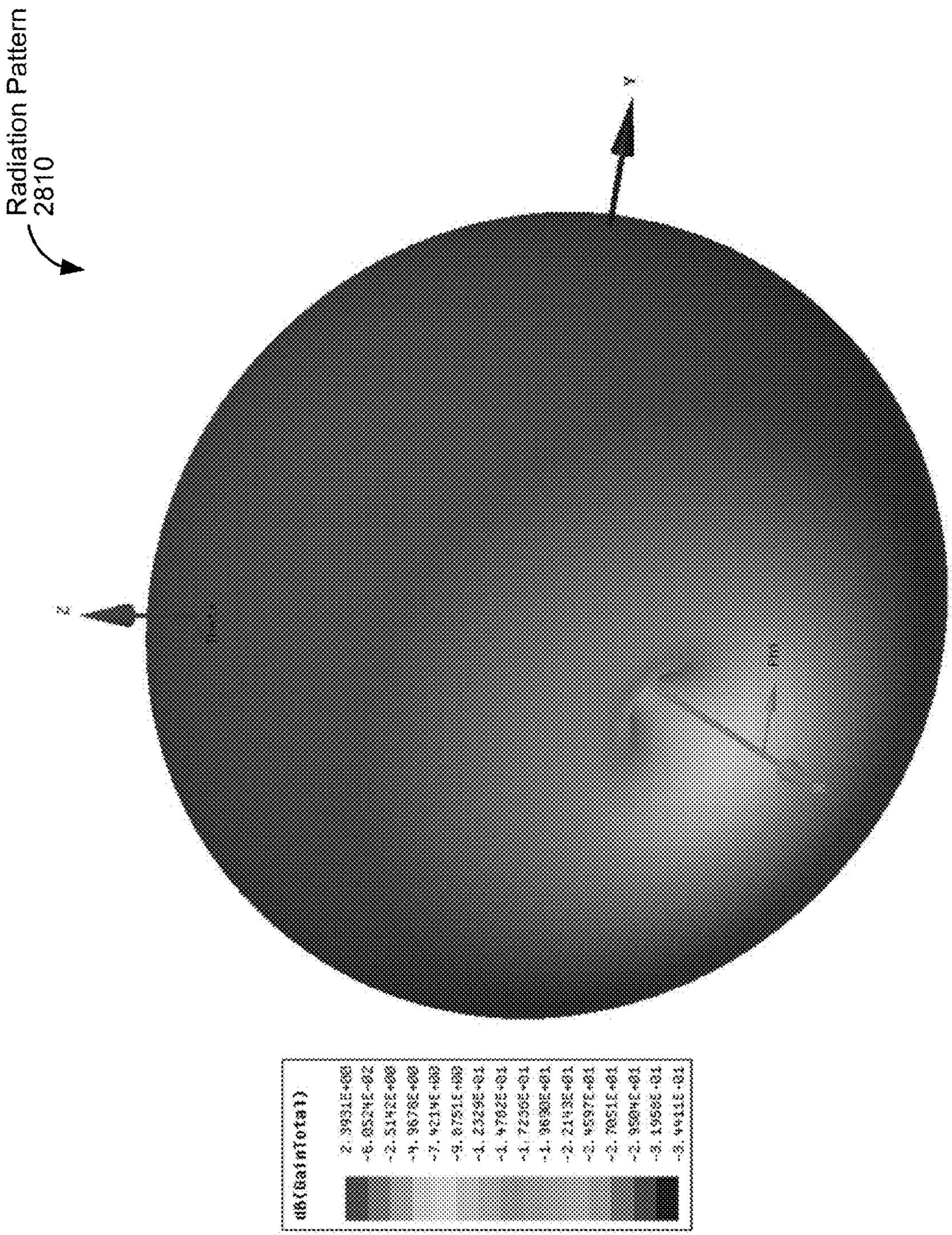

Radiation Pattern
2810
Y
Z
dB(GainTotal)
2.3931E+00
-6.0524E-02
-2.5142E+00
-4.9678E+00
-7.4214E+00
-9.8751E+00
-1.2329E+01
-1.4782E+01
-1.7236E+01
-1.9690E+01
-2.2143E+01
-2.4597E+01
-2.7051E+01
-2.9504E+01
-3.1958E+01
-3.4411E+01

Figure 28B

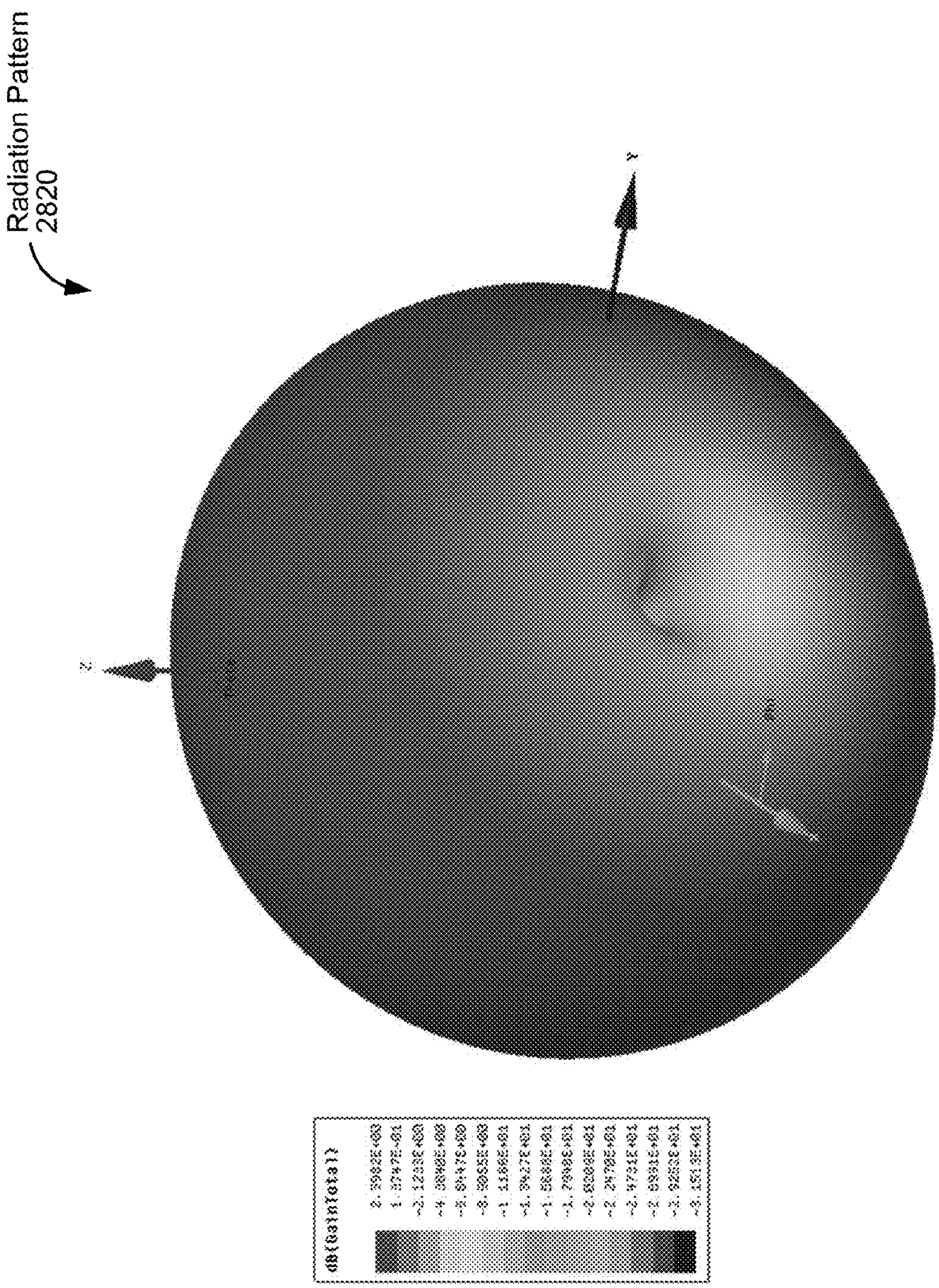


Figure 28C

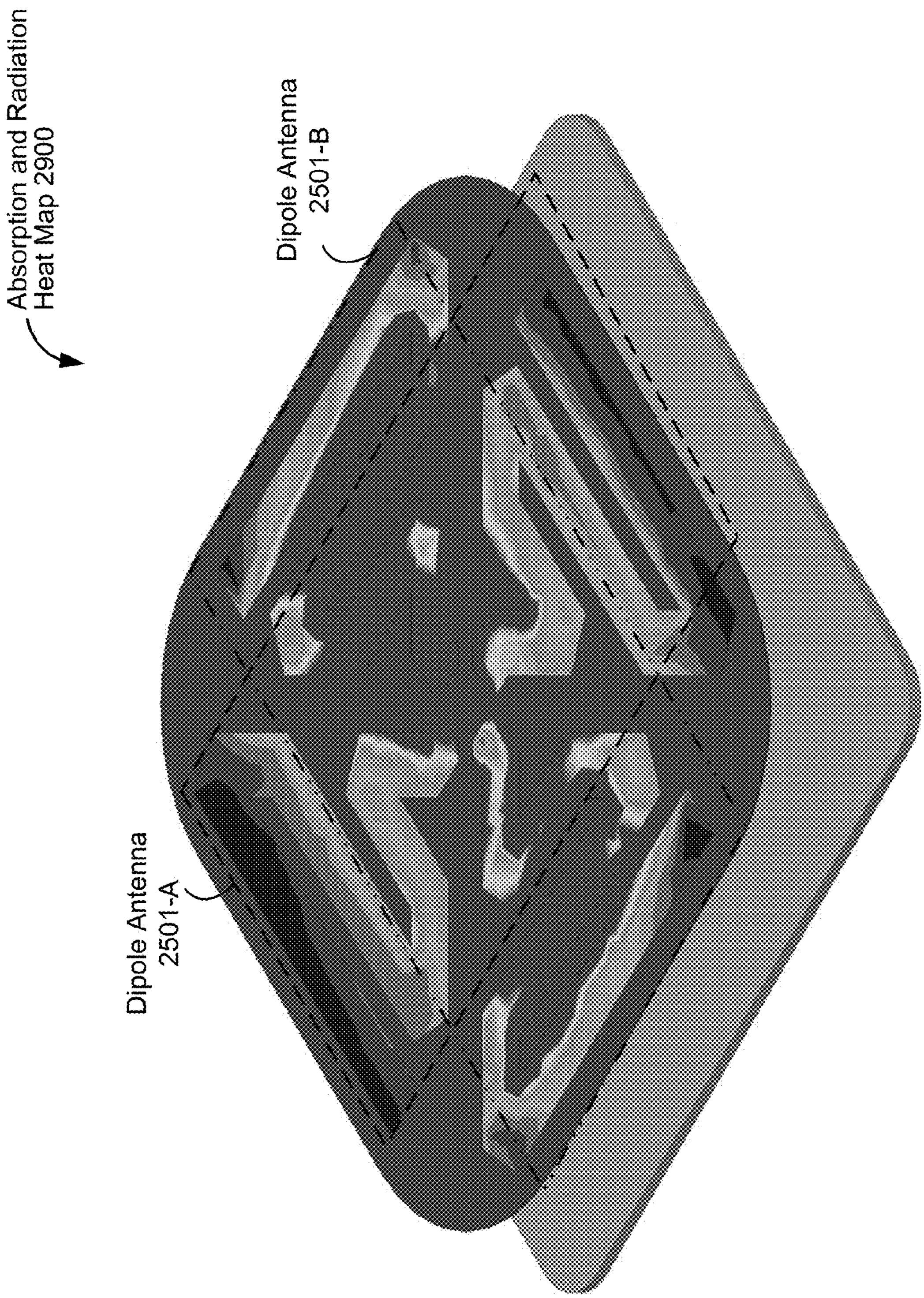

Absorption and Radiation
Heat Map 2900
Dipole Antenna
2501-B
Dipole Antenna
2501-A

Figure 29A

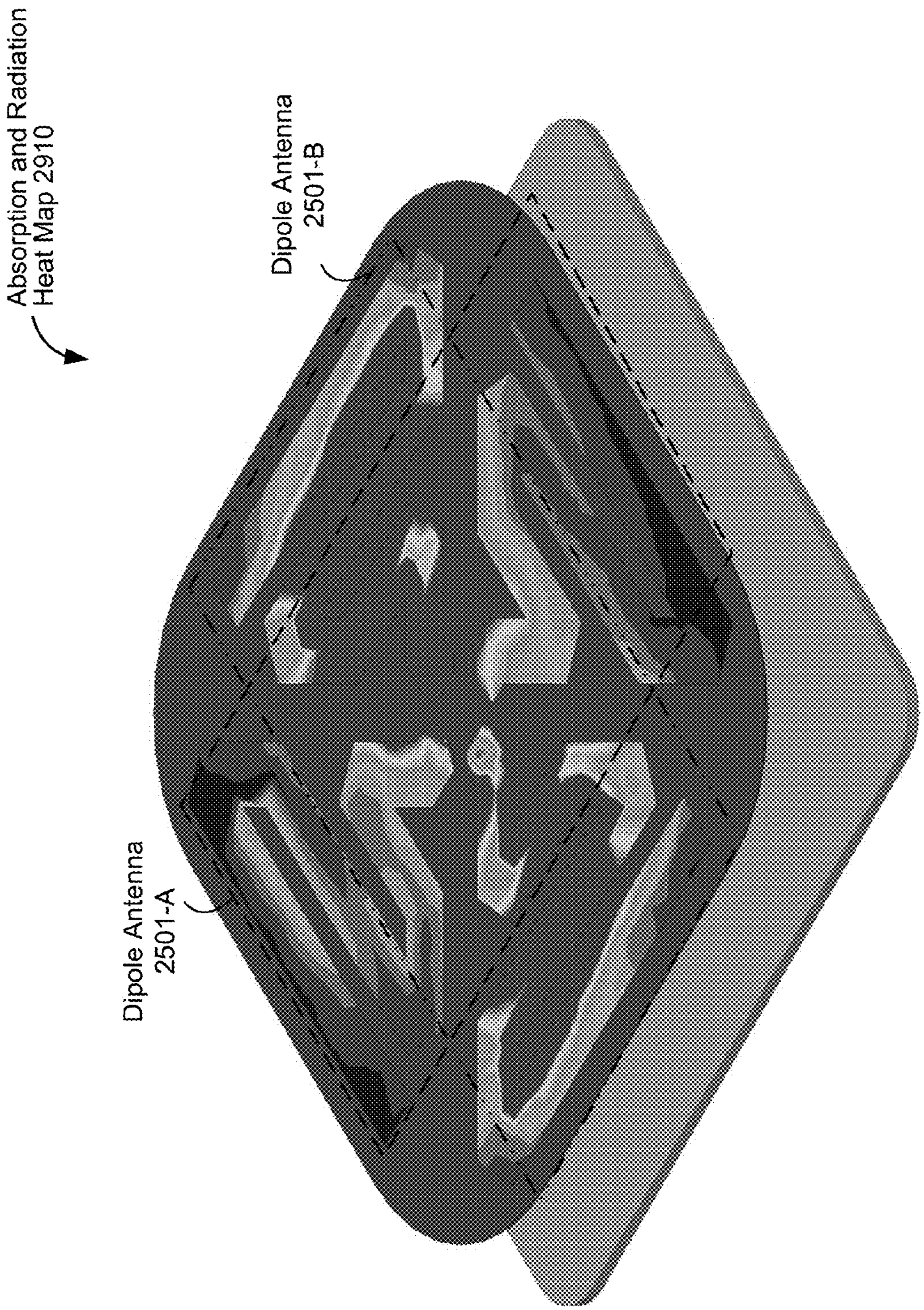

Absorption and Radiation
Heat Map 2910
Dipole Antenna
2501-B
Dipole Antenna
2501-A

Figure 29B

3000

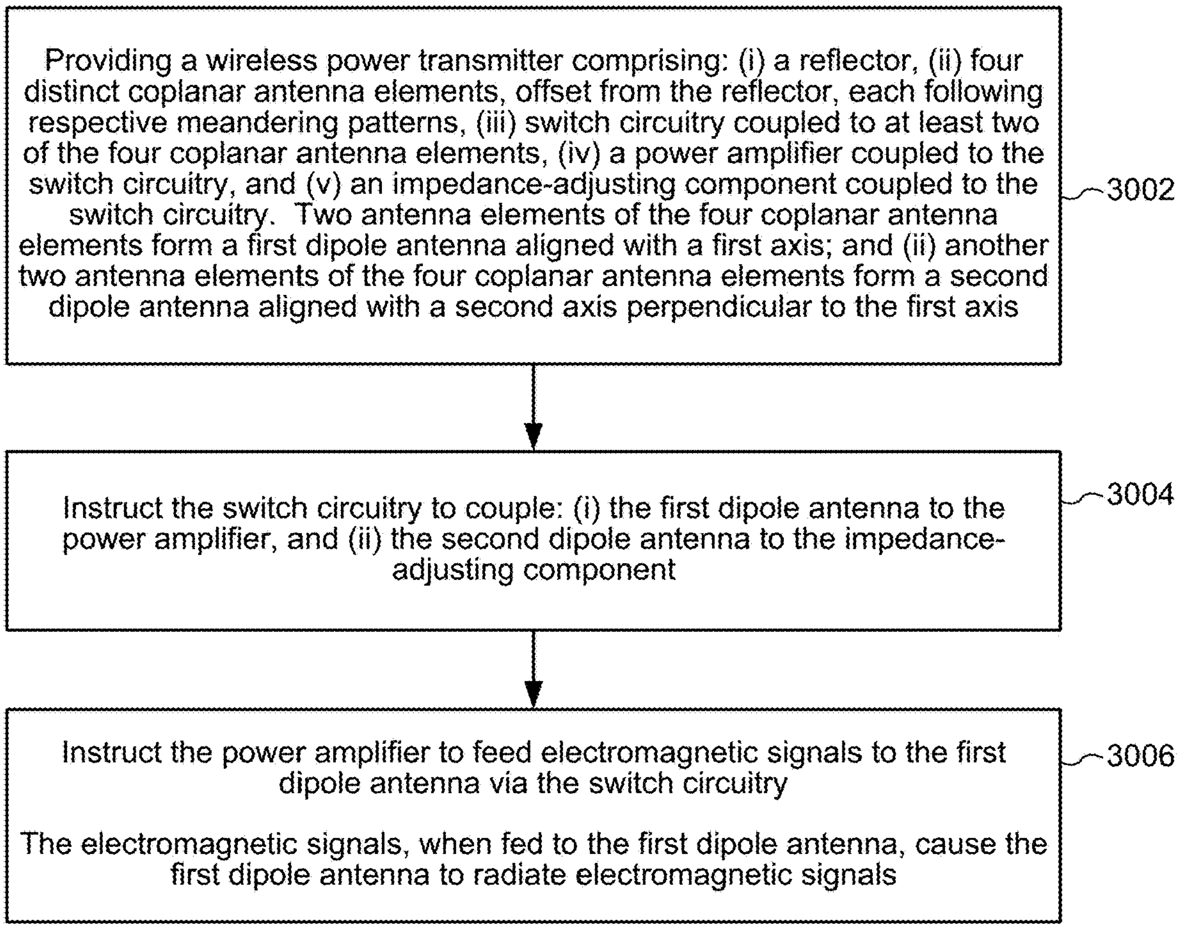


Figure 30

ELECTRONIC DEVICE WITH ANTENNA ELEMENTS THAT FOLLOW MEANDERING PATTERNS FOR RECEIVING WIRELESS POWER FROM A NEAR-FIELD ANTENNA

RELATED APPLICATIONS

This application is a continuation of U.S. Non-Provisional patent application Ser. No. 16/024,636, filed Jun. 29, 2018, which is:

a continuation-in-part of PCT Patent Application No. PCT/US17/65886, filed Dec. 12, 2017, which is a continuation of U.S. Non-Provisional patent application Ser. No. 15/833,790 (now U.S. Pat. No. 10,079, 515), filed Dec. 6, 2017, which is a continuation-in-part of U.S. Non-Provisional patent application Ser. No. 15/424,552 (now U.S. Pat. No. 10,256,677), filed Feb. 3, 2017, which claims priority to U.S. Provisional Application Ser. No. 62/433,227, filed Dec. 12, 2016. PCT Patent Application No. PCT/US17/65886 also claims priority to U.S. Provisional Application Ser. No. 62/541,581, filed Aug. 4, 2017, and

a continuation-in-part of U.S. Non-Provisional patent application Ser. No. 15/269,729 (now U.S. Pat. No. 10,320,446), filed Sep. 19, 2016, which (i) claims priority to U.S. Provisional Application Ser. No. 62/374,578, filed Aug. 12, 2016, and (ii) is also a continuation-in-part of U.S. Non-Provisional patent application Ser. No. 15/046,348 (now U.S. Pat. No. 10,027,158), filed Feb. 17, 2016, which claims priority to U.S. Provisional Application Ser. No. 62/387,205, filed Dec. 24, 2015. Each of these applications is hereby incorporated by reference in its respective entirety.

TECHNICAL FIELD

The embodiments herein generally relate to near-field wireless power transmission systems (e.g., antennas, software, and devices used in such systems) and, more specifically, to a near-field antenna for wireless power transmission with four coplanar antenna elements that each follows a respective meandering pattern.

BACKGROUND

Conventional charging pads utilize inductive coils to generate a magnetic field that is used to charge a device. Users typically must place the device at a specific position on the charging pad and are unable to move the device to different positions on the pad, without interrupting or terminating the charging of the device. This results in a frustrating experience for many users as they may be unable to locate the device at the exact right position on the pad in which to start charging their device. Often, users may think that their device has been properly positioned, but may then dishearteningly find hours later that very little (or no) energy has been transferred.

Conventional charging pads also utilize components that are distributed across multiple different integrated circuits. Such a configuration results in processing delays that cause these charging pads to operate slower (e.g., wireless charging and adjustments made during wireless charging takes longer) than is desired by users of such pads.

SUMMARY

Accordingly, there is a need for wireless charging systems (e.g., RF charging pads) that address the problems identified above. To this end, an RF charging pad is described herein that includes components that are efficiently arranged on a single integrated circuit, and that single integrated circuit manages antennas of the RF charging pad by selectively or sequentially activating antenna zones (e.g., one or more antennas or unit cell antennas of the RF charging pad that are grouped together, also referred to herein as an antenna group) to locate an efficient antenna zone to use for transmission of wireless power to a receiver device that is located on a surface of the RF charging pad. Such systems and methods of use thereof help to eliminate user dissatisfaction with conventional charging pads. For example, by monitoring transferred energy while selectively activating the antenna zones, such systems and methods of use thereof help to eliminate wasted RF power transmissions by ensuring that energy transfer is maximized at any point in time and at any position at which a device may be placed on an RF charging pad, thus eliminating wasteful transmissions that may not be efficiently received.

In the description that follows, references are made to an RF charging pad that includes various antenna zones. For the purposes of this description, antenna zones include one or more transmitting antennas of the RF charging pad, and each antenna zone may be individually addressable by a controlling integrated circuit (e.g., RF power transmitter integrated circuit **160**, FIGS. **1**A-**1**B) to allow for selective activation of each antenna zone in order to determine which antenna zone is able to most efficiently transfer wireless power to a receiver. The RF charging pad is also inter-changeably referred to herein as a near-field charging pad, or, more simply, as a charging pad.

(A1) In some embodiments, a method is performed at a near-field charging pad that includes a wireless communication component (e.g., communication component **204**, FIG. **1**A), a plurality of antenna zones that each respectively include at least one antenna element (e.g., example antenna zones are shown in FIG. **1**B), and one or more processors (e.g., CPU **202**, FIGS. **1**B and **2**A). The method includes detecting, via the wireless communication component, that a wireless power receiver is within a threshold distance of the near-field charging pad and in response to detecting that the wireless power receiver is within the threshold distance of the near-field charging pad, determining whether the wireless power receiver has been placed on the near-field charging pad. The method further includes, in accordance with determining that the wireless power receiver has been placed on the near-field charging pad, selectively transmitting, by respective antenna elements included in the plurality of antenna zones, respective test power transmission signals with a first set of transmission characteristics until a determination is made that a particular power-delivery parameter associated with transmission of a respective test power transmission signal by at least one particular antenna zone of the plurality of antenna zones satisfies power-delivery criteria. Upon determining, by the one or more processors, that the particular power-delivery parameter satisfies the power-delivery criteria, the method further includes transmitting a plurality of additional power transmission signals to the wireless power receiver using the at least one particular antenna zone, wherein each additional power transmission signal of the plurality is transmitted with a second set of transmission characteristics, distinct from the first set.

(A2) In some embodiments of the method of A1, determining whether the wireless power receiver has been placed on the surface of the near-field charging pad includes: (i) transmitting the test power transmission signals using each of the plurality of antenna zones, (ii) monitoring an amount of reflected power at the near-field charging pad while transmitting the test power transmission signals, and (iii) determining that the wireless power receiver has been placed on the near-field charging pad when the amount of reflected power satisfies a device detection threshold.

(A3) In some embodiments of the method of A2, the amount of reflected power is measured at each antenna zone of the plurality of antenna zones.

(A4) In some embodiments of the method of any of A2-A3, the device detection threshold is established during a calibration process for the near-field charging pad.

(A5) In some embodiments of the method of A4, the device detection threshold is specific to a type of device that is coupled with the wireless power receiver, and the device detection threshold is selected by the one or more processors after detecting the wireless power receiver in proximity to the near-field charging pad (e.g., the wireless power receiver sends a packet of information to the near-field charging pad, and that packet of information includes information that identifies the type of device that is coupled with the wireless power receiver).

(A6) In some embodiments of the method of any of A1-A5, selectively transmitting the respective test power transmission signals is performed using each antenna zone of the plurality of antenna zones. In addition, the method further comprises, before the determination is made that the power-delivery parameter associated with transmission of the respective test power transmission signal by the at least one particular antenna zone of the plurality of antenna zones satisfies the power-delivery criteria: (i) updating a respective power-delivery parameter associated with transmission of a respective test power transmission signal by each respective antenna zone based on the transmission by each antenna zone, and (ii) selecting two or more antenna zones, including the at least one particular antenna zone, based on their associated respective power-delivery parameters, to transmit wireless power to the wireless power receiver.

(A7) In some embodiments of the method of A6, the method further comprises using each of the two or more antenna zones to transmit additional test power transmission signals having the first set of transmission characteristics. Moreover, the determination that the particular power-delivery parameter satisfies the power-delivery criteria includes determining that the particular power-delivery parameter indicates that the particular antenna zone is more efficiently transmitting wireless power to the wireless power receiver as compared to other antenna zones of the two or more antenna zones.

(A8) In some embodiments of the method of any of A6-A7, the determination that the particular power-delivery parameter satisfies the power-delivery criteria also includes determining that the particular power-delivery parameter indicates that a first threshold amount of power is transferred to the wireless power receiver by the at least one particular antenna zone, and the at least one particular antenna zone is the only antenna zone of the two or more antenna zones having a respective power-delivery parameter that indicates that the first threshold amount of power is transferred to the wireless power receiver.

(A9) In some embodiments of the method of any of A6-A8, the determination that the particular power-delivery parameter satisfies the power-delivery criteria also includes determining that (i) no antenna zone is transferring a first threshold amount of power to the wireless power receiver and (ii) an additional power-delivery parameter associated with an additional antenna zone of the two or more antenna zones satisfies the power-delivery criteria. In addition, the particular power-delivery parameter indicates that a first amount of power transferred to the wireless power receiver by the particular antenna zone is above a second threshold amount of power and below the first threshold amount of power, and the additional power-delivery parameter indicates that a second amount of power transferred to the wireless power receiver by the additional antenna zone is above the second threshold amount of power and below the first threshold amount of power.

(A10) In some embodiments of the method of A9, both of the particular antenna group and the additional antenna group are used to simultaneously transmit the additional plurality of power transmission signals to provide power to the wireless power receiver.

(A11) In some embodiments of the method of any of A1-A10, information used to determine the power-delivery parameter is provided to the near-field charging pad by the wireless power receiver via the wireless communication component of the near-field charging pad.

(A12) In some embodiments of the method of any of A1-A11, the second set of transmission characteristics is determined by adjusting at least one characteristic in the first set of transmission characteristics to increase an amount of power that is transferred by the particular antenna group to the wireless power receiver.

(A13) In some embodiments of the method of A12, the at least one adjusted characteristic is a frequency or impedance value.

(A14) In some embodiments of the method of any of A1-A13, while transmitting the additional plurality of power transmission signals, adjusting at least one characteristic in the second set of transmission characteristics based on information, received from the wireless power receiver, that is used to determine a level of power that is wirelessly delivered to the wireless power receiver by the near-field charging pad.

(A15) In some embodiments of the method of any of A1-A14, the one or more processors are components of a single integrated circuit that is used to control operation of the near-field charging pad. For example, any of the methods described herein are managed by the single integrated circuit, such as an instance of the radio frequency (RF) power transmitter integrated circuit **160** shown in FIG. **1**B.

(A16) In some embodiments of the method of any of A1-A15, each respective power-delivery metric corresponds to an amount of power received by the wireless power receiver based on transmission of a respective test power transmission signal by a respective antenna group of the plurality of antenna groups.

(A17) In some embodiments of the method of any of A1-A16, the method further includes, before transmitting the test power transmission signals, determining that the wireless power receiver is authorized to receive wirelessly delivered power from the near-field charging pad.

(A18) In another aspect, a near-field charging pad is provided. In some embodiments, the near-field charging pad includes a wireless communication component, a plurality of antenna zones that each respectively include at least one antenna element, one or more processors, and memory storing one or more programs, which when executed by the one or more processors cause the near-field charging pad to perform the method described in any one of A1-A17.

(A19) In yet another aspect, a near-field charging pad is provided and the near-field charging includes means for performing the method described in any one of A1-A17.

(A20) In still another aspect, a non-transitory computer-readable storage medium is provided. The non-transitory computer-readable storage medium stores executable instructions that, when executed by a near-field charging pad (that includes a wireless communication component, a plurality of antenna zones that each respectively include at least one antenna element) with one or more processors/cores, cause the near-field charging pad to perform the method described in any one of A1-A17.

As described above, there is also a need for an integrated circuit that includes components for managing transmission of wireless power that are all integrated on a single integrated circuit. Such a integrated circuit and methods of use thereof help to eliminate user dissatisfaction with conventional charging pads. By including all components on a single chip (as discussed in more detail below in reference to FIGS. **1**A and **1**B), such integrated circuits are able to manage operations at the integrated circuits more efficiently and quickly (and with lower latency), thereby helping to improve user satisfaction with the charging pads that are managed by these integrated circuits.

(B1) In some embodiments, an integrated circuit includes: (i) a processing unit that is configured to control operation of the integrated circuit, (ii) a power converter, operatively coupled to the processing unit, that is configured to convert an input current into radio frequency energy, (iii) a waveform generator, operatively coupled to the processing unit, that is configured to generate a plurality of power transmission signals using the radio frequency energy, (iv) a first interface that couples the integrated circuit with a plurality of power amplifiers that are external to the integrated circuit, and (v) a second interface, distinct from the first interface, that couples the integrated circuit with a wireless communication component. The processing unit is also configured to: (i) receive, via the second interface, an indication that a wireless power receiver is within transmission range of a near-field charging pad controlled by the integrated circuit, and (ii) in response to receiving the indication provide, via the first interface, at least some of the plurality of power transmission signals to at least one of the plurality of power amplifiers.

(B2) In some embodiments of the integrated circuit of B1, the processing unit includes a CPU, ROM, RAM, and encryption (e.g., CPU subsystem **170**, FIG. **1**B).

(B3) In some embodiments of the integrated circuit of any of B1-B2, the input current is direct current. Alternatively, in some embodiments, the input current is alternating current. In these embodiments, the power converter is a radio frequency DC-DC converter or a radio frequency AC-AC converter, respectively.

(B4) In some embodiments of the integrated circuit of any of B1-B3, the wireless communication component is a Bluetooth or Wi-Fi radio that is configured to receive communication signals from a device that is placed on a surface of the near-field charging pad.

To help address the problems described above and to thereby provide charging pads that satisfy user needs, the antenna zones described above may include adaptive antenna elements (e.g., antenna zones **290** of the RF charging pad **100**, FIG. **1**B, may each respectively include one or more of the antennas **120** described below in reference to FIGS. **3**A-**6**E and **8**) that are able to adjust energy transmission characteristics (e.g., impedance and frequency for a conductive line of a respective antenna element) so that the charging pad is capable of charging a device that is placed at any position on the pad.

In accordance with some embodiments, the antenna zones of the radio frequency (RF) charging pads described herein may include: one or more antenna elements that are in communication with the one or more processors for transmitting RF signals to the RF receiver of the electronic device. In some embodiments, each respective antenna element includes: (i) a conductive line forming a meandered line pattern; (ii) a first terminal at a first end of the conductive line for receiving current that flows through the conductive line at a frequency controlled by the one or more processors; and (iii) a second terminal, distinct from the first terminal, at a second end of the conductive line, the second terminal coupled with a component that is controlled by the at least one processor and allows for modifying an impedance value at the second terminal. In some embodiments, the at least one processor is configured to adaptively adjust the frequency and/or the impedance value to optimize the amount of energy that is transferred from the one or more antenna elements to the RF receiver of the electronic device.

There is a need for wireless charging systems (e.g., RF charging pads) that include adaptive antenna elements that are able to adjust energy transmission characteristics (e.g., impedance and frequency for a conductive line of a respective antenna element) so that the charging pad is capable of charging a device that is placed at any position on the pad. In some embodiments, these charging pads include one or more processors that monitor energy transferred from the transmitting antenna elements (also referred to herein as RF antenna elements or antenna elements) and to a receiver of an electronic device to be charged, and the one or more processors optimize the energy transmission characteristics to maximize energy transfer at any position on the charging pad. Some embodiments may also include a feedback loop to report received power at the receiver to the one or more processors.

(C1) In accordance with some embodiments, a radio frequency (RF) charging pad is provided. The RF charging pad includes: at least one processor for monitoring an amount of energy that is transferred from the RF charging pad to an RF receiver of an electronic device. The RF charging pad also includes: one or more antenna elements that are in communication with the one or more processors for transmitting RF signals to the RF receiver of the electronic device. In some embodiments, each respective antenna element includes: (i) a conductive line forming a meandered line pattern; (ii) a first terminal at a first end of the conductive line for receiving current that flows through the conductive line at a frequency controlled by the one or more processors; and (iii) a second terminal, distinct from the first terminal, at a second end of the conductive line, the second terminal coupled with a component that is controlled by the at least one processor and allows for modifying an impedance value at the second terminal. In some embodiments, the at least one processor is configured to adaptively adjust the frequency and/or the impedance value to optimize the amount of energy that is transferred from the one or more antenna elements to the RF receiver of the electronic device.

(C2) In accordance with some embodiments, a method is also provided that is used to charge an electronic device through radio frequency (RF) power transmission. The method includes: providing a transmitter comprising at least one RF antenna. The method also includes: transmitting, via at the least one RF antenna, one or more RF signals and monitoring an amount of energy that is transferred via the one or more RF signals from the at least one RF antenna to an RF receiver. The method additionally includes: adaptively adjusting a characteristic of the transmitter to optimize the amount of energy that is transferred from the at least one RF antenna to the RF receiver. In some embodiments, the characteristic is selected from a group consisting of (i) a frequency of the one or more RF signals, (ii) an impedance of the transmitter, and (iii) a combination of (i) and (ii). In some embodiments, the at least one RF antenna is a part of an array of RF antennas.

(C3) In accordance with some embodiments, a radio frequency (RF) charging pad is provided. The RF charging pad includes: one or more processors for monitoring an amount of energy that is transferred from the RF charging pad to an RF receiver of an electronic device. The RF charging pad also includes: one or more transmitting antenna elements that are configured to communicate with the one or more processors for transmitting RF signals to the RF receiver of the electronic device. In some embodiments, each respective antenna element includes: (i) a conductive line forming a meandered line pattern; (ii) an input terminal at a first end of the conductive line for receiving current that flows through the conductive line at a frequency controlled by the one or more processors; and (iii) a plurality of adaptive load terminals, distinct from the input terminal and distinct from each other, at a plurality of positions of the conductive line, each respective adaptive load terminal of the plurality of adaptive load terminals coupled with a respective component that is configured to be controlled by the one or more processors and is configured to allow modifying a respective impedance value at the respective adaptive load terminal. In some embodiments, the one or more processors are configured to adaptively adjust at least one of the frequency and a respective impedance value at one or more of the plurality of adaptive load terminals to optimize the amount of energy that is transferred from the one or more transmitting antenna elements to the RF receiver of the electronic device.

(C4) In accordance with some embodiments, a method is also provided that is used to charge an electronic device through radio frequency (RF) power transmission. The method includes: providing a charging pad that includes a transmitter comprising one or more RF antennas. In some embodiments, each RF antenna includes: (i) a conductive line forming a meandered line pattern; (ii) an input terminal at a first end of the conductive line for receiving current that flows through the conductive line at a frequency controlled by one or more processors; and (iii) a plurality of adaptive load terminals, distinct from the input terminal and distinct from each other, at a plurality of positions of the conductive line, each respective adaptive load terminal of the plurality of adaptive load terminals coupled with a respective component that is controlled by the one or more processors and allows for modifying a respective impedance value at the respective adaptive load terminal. The method also includes: transmitting, via the one or more RF antennas, one or more RF signals, and monitoring an amount of energy that is transferred via the one or more RF signals from the one or more RF antennas to an RF receiver. The method additionally includes: adaptively adjusting a characteristic of the transmitter using the one or more processors of the transmitter to optimize the amount of energy that is transferred from the one or more RF antennas to the RF receiver. In some embodiments, the characteristic is selected from a group consisting of (i) a frequency of the one or more RF signals, (ii) an impedance of the transmitter, and (iii) a combination of (i) and (ii). In some embodiments, the impedance of the transmitter is adaptively adjusted at a respective one or more of the plurality of adaptive load terminals of the one or more RF antennas using the one or more processors of the transmitter.

(C5) In accordance with some embodiments, a non-transitory computer-readable storage medium is provided. The non-transitory computer-readable storage medium includes executable instructions that, when executed by one or more processors that are coupled with a radio frequency (RF) charging pad that includes one or more transmitting antenna elements, cause the one or more processors to: monitor an amount of energy that is transferred from the RF charging pad to an RF receiver of an electronic device; and communication with the one or more transmitting antenna elements for transmitting RF signals to the RF receiver of the electronic device. In some embodiments, each respective transmitting antenna element includes: a conductive line forming a meandered line pattern; an input terminal at a first end of the conductive line for receiving current that flows through the conductive line at a frequency controlled by the one or more processors; and a plurality of adaptive load terminals, distinct from the input terminal and distinct from each other, at a plurality of positions of the conductive line, each respective adaptive load terminal of the plurality of adaptive load terminals coupled with a respective component that is configured to be controlled by the one or more processors and is configured to allow modifying a respective impedance value at each respective adaptive load terminal. And the one or more processors further adaptively adjust at least one of the frequency and a respective impedance value at one or more of the plurality of adaptive load terminals to optimize the amount of energy that is transferred from the one or more transmitting antenna elements to the RF receiver of the electronic device.

(C6) In some embodiments of any of C1-05, the frequency is in a first frequency band, and at least one of the one or more transmitting antenna elements is configured to operate at a second frequency band based on adaptive adjustments, by the one or more processors, to respective impedance values at one or more of the plurality of adaptive load terminals of the at least one transmitting antenna element.

(C7) In some embodiments of any of C1-C6, the RF charging pad includes an input circuit that is coupled with the one or more processors and is configured to provide the current to the input terminal at the first end of the conductive line, wherein the one or more processors are configured to adaptively adjust the frequency by instructing the input circuit to generate the current with a new frequency that is distinct from the frequency.

(C8) In some embodiments of any of C1-C7, the one or more processors are configured to adaptively adjust the frequency by instructing the feeding element to generate the current with a plurality of different frequencies that are determined using predetermined increments.

(C9) In some embodiments of any of C1-C8, a respective conductive line for at least one of the one or more transmitting antenna elements has a respective meandered line pattern that allows the at least one transmitting antenna element to efficiently transmit RF signals having the frequency and/or the new frequency, at least two adjacent segments of the respective conductive line having the respective meandered line pattern have different geometric dimensions relative to each other, and the respective conductive line has a length that remains the same when the at least one transmitting antenna element is configured to transmit RF signals having the frequency and/or the new frequency.

(C10) In some embodiments of any of C1-C9, at least one transmitting antenna element of the one or more transmitting antenna elements has a first segment and a second segment, the first segment including the input terminal, and the at least one transmitting antenna element is configured to: operate at the frequency while the first segment is not coupled with the second segment, and operate at the new frequency while the first segment is coupled with the second segment; and the one or more processors are configured to couple the first segment with the second segment in conjunction with instructing the feeding element to generate the current with the new frequency that is distinct from the frequency.

(C11) In some embodiments of any of C1-C10, the one or more processors are configured to: adaptively adjust the frequency and/or a respective impedance value associated with a first transmitting antenna element of the one or more transmitting antenna elements to cause the first transmitting antenna element to operate in a first frequency band, and adaptively adjust the frequency and/or the respective impedance value associated with a second transmitting antenna element of the one or more transmitting antenna elements to cause the second transmitting antenna element to operate in a second frequency band, wherein the first frequency band is distinct from the second frequency band.

(C12) In some embodiments of any of C1-C11, the electronic device is placed in contact with or close to a top surface of the RF charging pad.

(C13) In some embodiments of any of C1-C12, the respective component is a mechanical relay coupled with the respective adaptive load terminal for switching the respective adaptive load terminal between open and short states, and the impedance value is adaptively adjusted at the respective adaptive load terminal of the respective transmitting antenna element by opening or closing the mechanical relay to switch between an open or short circuit, respectively.

(C14) In some embodiments of any of C1-C13, the respective component is an application-specific integrated circuit (ASIC), and the respective impedance value is adaptively adjusted by the ASIC to within a range of values.

(C15) In some embodiments of any of C1-C14, the one or more processors are configured to: adaptively adjust the frequency and/or the respective impedance value by adaptively adjusting the frequency and a respective impedance value at one or more of the plurality of adaptive load terminals to determine a relative maximum amount of energy that is transferred to the RF receiver of the electronic device, and once the maximum amount of energy is determined, cause each of the one or more transmitting antenna elements to respectively transmit the RF signals at a respective frequency and using a respective impedance value that resulted in the maximum amount of energy transferred to the RF receiver.

(C16) In some embodiments of any of C1-C15, the one or more processors monitor the amount of energy that is transferred to the RF receiver based at least in part on information received from the electronic device, the information identifying energy received at the RF receiver from the RF signals.

(C17) In some embodiments of any of C1-C16, the information received from the electronic device identifying received energy is sent using a wireless communication protocol.

(C18) In some embodiments of any of C1-C17, the wireless communication protocol is bluetooth low energy (BLE).

(C19) In some embodiments of any of C1-C18, the one or more processors monitor the amount of energy transferred based at least in part on an amount of energy that is detected at the respective adaptive load terminal.

Thus, wireless charging systems configured in accordance with the principles described herein are able to charge an electronic device that is placed at any position on the RF charging pad and avoid wasting energy by ensuring that energy transfer is constantly optimized.

In addition, wireless charging systems configured in accordance with the principles described herein are able to charge different electronic devices that are tuned at different frequencies or frequency bands on the same charging transmitter. In some embodiments, a transmitter with a single antenna element can operate at multiple frequencies or frequency bands at the same time or at different times. In some embodiments, a transmitter with multiple antenna elements can operate at multiple frequencies or frequency bands at the same time. That enables more flexibility in the types and sizes of antennas that are included in receiving devices.

In another aspect, dynamically-adjustable transmitting antennas are provided. In the design of charging pads that allow receiving devices to be placed at any position on the pad, radio-frequency-based solutions offer much promise. Because receiving antennas used in radio-frequency-based solutions may have different polarizations, transmitting antennas must also be designed that are able to transmit at different polarizations, to ensure an efficient transfer of power from the transmitting to the receiving antennas. As such, there is a need for transmitting antennas that may be dynamically adjusted to transmit energy using different polarizations and embodiments discussed herein address this need (see, e.g., descriptions and figures associated with near-field antenna **2500**).

(D1) In accordance with some embodiments, a near-field antenna is provided. The near-field antenna (e.g., near-field antenna **2500**, FIG. **25**A) includes: a reflector and four distinct coplanar antenna elements, offset from the reflector, where each of the four distinct antenna elements follows respective meandering patterns. Further, two antenna elements of the four coplanar antenna elements form a first dipole antenna along a first axis, and another two antenna elements of the four coplanar antenna elements form a second dipole antenna along a second axis perpendicular to the first axis. The near-field antenna further includes: (i) a power amplifier configured to feed electromagnetic signals to at least one of the first and second dipole antennas, (ii) an impedance-adjusting component configured to adjust an impedance of at least one of the first and second dipole antennas, and (iii) switch circuitry coupled to the power amplifier, the impedance-adjusting component, and the first and second dipole antennas. The switch circuitry is configured to: (A) switchably couple the first dipole antenna to the power amplifier and the second dipole antenna to the impedance-adjusting component, or (B) switchably couple the second dipole antenna to the power amplifier and the first dipole antenna to the impedance-adjusting component.

(D2) In accordance with some embodiments, a method is also provided that is used to charge an electronic device through radio frequency (RF) power transmission using a near-field antenna. The method includes providing the near-field antenna of D1. For example, the near-field antenna includes (i) a reflector, (ii) four distinct coplanar antenna elements, offset from the reflector, each of the four distinct antenna elements following respective meandering patterns, where: (A) two antenna elements of the four coplanar antenna elements form a first dipole antenna aligned with a first axis, and (B) another two antenna elements of the four coplanar antenna elements form a second dipole antenna aligned with a second axis perpendicular to the first axis, (iii) switch circuitry coupled to at least two of the four coplanar antenna elements, (iv) a power amplifier coupled to the switch circuitry, and (v) an impedance-adjusting component coupled to the switch circuitry. The method further includes instructing the switch circuitry to couple: (i) the first dipole antenna to the power amplifier, and (ii) the second dipole antenna to the impedance-adjusting component. The method further includes instructing the power amplifier to feed electromagnetic signals to the first dipole antenna via the switch circuitry. In doing so, the electromagnetic signals, when fed to the first dipole antenna, cause the first dipole antenna to radiate electromagnetic signals to be received by a wireless-power-receiving device located within a threshold distance from the near-field antenna. In addition, an impedance of the second dipole antenna is adjusted by the impedance-adjusting component so that the impedance of the second dipole antenna differs from an impedance of the first dipole antenna.

(D3) In accordance with some embodiments, a non-transitory computer-readable storage medium is provided. The non-transitory computer-readable storage medium includes executable instructions that, when executed by one or more processors that are coupled with the near-field antenna of D1, cause the near-field antenna of D1 to: (A) instruct the switch circuitry to couple: (i) the first dipole antenna to the power amplifier, and (ii) the second dipole antenna to the impedance-adjusting component, and (B) instruct the power amplifier to feed electromagnetic signals to the first dipole antenna via the switch circuitry. In doing so, the electromagnetic signals, when fed to the first dipole antenna, cause the first dipole antenna to radiate electromagnetic signals to be received by a wireless-power-receiving device located within a threshold distance from the near-field antenna. In addition, an impedance of the second dipole antenna is adjusted by the impedance-adjusting component so that the impedance of the second dipole antenna differs from an impedance of the first dipole antenna.

(D4) In some embodiments of any of D1-D3, in a first mode of operation for the near-field antenna, the switch circuitry couples (i) the first dipole antenna to the power amplifier and (ii) the second dipole antenna to the impedance-adjusting component. Further, in a second mode of operation for the near-field antenna, the switch circuitry couples (i) the second dipole antenna to the power amplifier and (ii) the first dipole antenna to the impedance-adjusting component.

(D5) In some embodiments of D4, in the first mode of operation for the near-field antenna, the first dipole antenna is to receive electromagnetic waves from the power amplifier and radiate the received electromagnetic waves having a first polarization, and in the second mode of operation for the near-field antenna, the second dipole antenna is to receive electromagnetic waves from the power amplifier and radiate the received electromagnetic waves having a second polarization different from the first polarization.

(D6) In some embodiments of any of D1-D5, a wireless-power-receiving device, located within a threshold distance from the near-field antenna, is configured to harvest the radiated electromagnetic waves and use the harvested electromagnetic waves to power or charge an electronic device coupled with the wireless-power-receiving device.

(D7) In some embodiments of any of D1-D6, the near-field antenna further includes a controller configured to control operation of the switch circuitry and the power amplifier.

(D8) In some embodiments of any of D1-D7, the controller is configured to control operation of the switch circuitry and the power amplifier based on one or more of: (i) a location of a wireless-power-receiving device, (ii) a polarization of a power-receiving-antenna of the wireless-power-receiving device, and (iii) a spatial orientation of the wireless-power-receiving device.

(D9) In some embodiments of any of D1-D8, the near-field antenna further includes a first feed and a second feed. The first feed is connected to a first of the two antenna elements of the first dipole antenna and the switch circuitry, and the first feed is configured to supply electromagnetic signals to the first antenna element of the first dipole antenna that originate from the power amplifier when the power amplifier is switchably coupled to the first dipole antenna by the switch circuitry (e.g., the near-field antenna is in the first mode of operation). The second feed is connected to a first of the other two antenna elements of the second dipole antenna and the switch circuitry, and the second feed is configured to supply electromagnetic signals to the first antenna element of the second dipole antenna that originate from the power amplifier when the power amplifier is switchably coupled to the second dipole antenna by the switch circuitry (e.g., the near-field antenna is in the second mode of operation).

(D10) In some embodiments of any of D1-D9, a first antenna element of the four distinct coplanar antenna elements is a first pole of the first dipole antenna and a second antenna element of the four distinct coplanar antenna elements is a second pole of the first dipole antenna. In addition, a third antenna element of the four distinct coplanar antenna elements is a first pole of the second dipole antenna and a fourth antenna element of the four distinct coplanar antenna elements is a second pole of the second dipole antenna.

(D11) In some embodiments of any of D1-D10, the two antenna elements that form the first dipole antenna each include two segments that are perpendicular to the first axis and the other two antenna elements that form the second dipole antenna each include two segments that are parallel to the first axis. Put another way, the two antenna elements that form the first dipole antenna each include two segments that are parallel to the second axis and the other two antenna elements that form the second dipole antenna each include two segments that are perpendicular to the second axis.

(D11.1) In some embodiments of any of D1-D11, each of the four distinct antenna elements includes: (i) a respective first plurality of segments, and (ii) a respective second plurality of segments interspersed between each of the first plurality of segments.

(D12) In some embodiments of any of D1-D11.1, first lengths of segments in the first plurality of segments increase from a first end portion of the antenna element to a second end portion of the antenna element and seconds lengths of segments in the second plurality of segments increase from the first end portion of the antenna element to the second end portion of the antenna element.

(D13) In some embodiments of D12, the first lengths of the segments in the first plurality of segments are different from the second lengths of the segments in the second plurality of segments.

(D14) In some embodiments of any of D12 and D13, the first lengths of the segments in the first plurality of segments are different from the second lengths of the segments in the second plurality of segments.

(D15) In some embodiments of D14, the first lengths of the segments in the first plurality of segments toward the second end portion of the antenna element are greater than the second lengths of the segments in the second plurality of segments toward the second end portion of the antenna element.

(D16) In some embodiments of any of D1-D15, the reflector is a solid metal sheet of copper or a copper alloy.

(D17) In some embodiments of any of D1-D16, the reflector is configured to reflect at least a portion of the electromagnetic signals radiated by the first or second dipole antennas.

(D18) In some embodiments of any of D1-D17, the four distinct coplanar antenna elements are formed on or within a substrate.

(D19) In some embodiments of D18, the substrate comprises a metamaterial of a predetermined magnetic permeability or electrical permittivity.

(D20) In some embodiments of any of D1-D19, the respective meandering patterns are all the same.

(D21) In some embodiments of D20, the two antenna elements that form the first dipole antenna are aligned along the first axis such that the respective meandering patterns followed by each of the two antenna elements are mirror images of one another.

(D22) In some embodiments of any of D20-D21, the other two antenna elements that form the second dipole antenna are aligned along the second axis such that the respective meandering patterns followed by each of the other two antenna elements are mirror images of one another.

(D23) In some embodiments of any of D1-D22, a first end portion of the respective meandering pattern followed by each of the four distinct antenna elements borders a same central portion of the near-field antenna, and a second end portion of the respective meandering pattern followed by each of the four distinct antenna elements borders a distinct edge of the near-field antenna. Furthermore, a longest dimension of the respective meandering pattern followed by each of the four distinct antenna elements is closer to the distinct edge of the near-field antenna than to the same central portion of the near-field antenna.

(D24) In some embodiments of D23, a shortest dimension of the respective meandering pattern followed by each of the four distinct antenna elements is closer to the same central portion of the near-field antenna than the distinct edge of the near-field antenna.

(E1) In accordance with some embodiments, a near-field antenna is provided. The near-field antenna (e.g., near-field antenna **2500**, FIG. **25**A) includes four distinct coplanar antenna elements, where each antenna element occupies a distinct quadrant of the near-field antenna (e.g., one of the quadrants **2570**-A to **2570**-D). Further, a width of each of the four distinct antenna elements increases, in a meandering fashion, from a central portion of the near-field antenna to a respective edge of the near-field antenna. In other words, a longest dimension of each of the four distinct antenna elements is near (i.e., adjacent/borders) the respective edge of the near-field antenna, and conversely, a shortest dimension of each of the four distinct antenna elements is near (i.e., adjacent/borders) the central portion of the near-field antenna.

(E2) In some embodiments of E1, two antenna elements of the four coplanar antenna elements form a first dipole antenna along a first axis, and another two antenna elements of the four coplanar antenna elements form a second dipole antenna along a second axis perpendicular to the first axis.

(E3) In some embodiments of E2, the two antenna elements that form the first dipole antenna are aligned along the first axis such that the respective meandering patterns followed by each of the two antenna elements are mirror images of one another.

(E4) In some embodiments of E3, the other two antenna elements that form the second dipole antenna are aligned along the second axis such that the respective meandering patterns followed by each of the other two antenna elements are mirror images of one another.

Note that the various embodiments described above can be combined with any other embodiments described herein. The features and advantages described in the specification are not all inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and not intended to circumscribe or limit the inventive subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

So that the present disclosure can be understood in greater detail, a more particular description may be had by reference to the features of various embodiments, some of which are illustrated in the appended drawings. The appended drawings, however, merely illustrate pertinent features of the present disclosure and are therefore not to be considered limiting, for the description may admit to other effective features.

FIG. **1**A is a block diagram of an RF wireless power transmission system, in accordance with some embodiments.

FIG. **1**B is a block diagram showing components of an example RF charging pad that includes an RF power transmitter integrated circuit and antenna zones, in accordance with some embodiments.

FIG. **1**C is a block diagram showing components of an example RF charging pad that includes an RF power transmitter integrated circuit coupled to a switch, in accordance with some embodiments.

FIG. **2**A is a block diagram illustrating an example RF charging pad, in accordance with some embodiments.

FIG. **2**B is a block diagram illustrating an example receiver device, in accordance with some embodiments.

FIG. **3**A is a high-level block diagram of an RF charging pad, in accordance with some embodiments.

FIGS. **3**B-**3**C are high-level block diagrams showing a portion of an RF charging pad, in accordance with some embodiments.

FIG. **3**D is a block diagram of a simplified circuit that illustrates energy flow within sections of an antenna element that is transmitting an RF signal, in accordance with some embodiments.

FIG. **4** is a schematic of a transmitting antenna element with two terminals, in accordance with some embodiments.

FIG. **5** is a flow chart of a method of charging an electronic device through radio frequency (RF) power transmission.

FIGS. **6**A-**6**E are schematics showing various configurations for individual antenna elements within an RF charging pad, in accordance with some embodiments.

FIGS. **7**A-**7**D are schematics of an antenna element for an RF receiver, in accordance with some embodiments.

FIG. **8** is a schematic of an RF charging pad with a plurality of transmitting antenna elements (or unit cells), in accordance with some embodiments.

FIGS. **9**A-**9**B are flow diagrams showing a method **900** of selectively activating one or more antenna zones in a near-field charging pad, in accordance with some embodiments.

FIG. **10** is an overview showing a process of selectively activating one or more antenna zones in a near-field charging pad, in accordance with some embodiments.

FIGS. **11**A-**11**E are flow diagrams showing various aspects of selectively activating one or more antenna zones in a near-field charging pad, in accordance with some embodiments.

FIG. **12** is a schematic of a transmitting antenna element with a plurality of adaptive loads of an RF charging pad, in accordance with some embodiments.

FIG. **13** is a flow chart of a method of charging an electronic device through radio frequency (RF) power transmission by using at least one RF antenna with a plurality of adaptive loads, in accordance with some embodiments.

FIGS. **14**A-**14**D are schematics showing various configurations for individual antenna elements that can operate at multiple frequencies or frequency bands within an RF charging pad, in accordance with some embodiments.

FIG. **15** is schematic showing an example configuration for an individual antenna element that can operate at multiple frequencies or frequency bands by adjusting the length of the antenna element, in accordance with some embodiments.

FIGS. **16**A and **16**B are schematic illustrations of an exemplary system, according to an embodiment.

FIGS. **17**A-**17**D are schematic illustrations of an exemplary system, according to an embodiment.

FIG. **18** is a schematic illustration of an exemplary system, according to an embodiment.

FIG. **19** is a schematic illustration of an exemplary system, according to an embodiment.

FIG. **20** is a schematic illustration of an exemplary system, according to an embodiment.

FIG. **21** is a schematic illustration of an exemplary system, according to an embodiment.

FIG. **22** is a schematic illustration of an exemplary system, according to an embodiment.

FIG. **23** is a schematic illustration of an exemplary system, according to an embodiment.

FIGS. **24**A and **24**B are schematic illustrations of an exemplary system, according to an embodiment.

FIG. **25**A shows an isometric view of a near-field antenna in accordance with some embodiments.

FIG. **25**B shows another isometric view of a near-field antenna in accordance with some embodiments.

FIGS. **25**C-**25**D show different side views of a near-field antenna in accordance with some embodiments.

FIG. **25**E shows another side view of a near-field antenna in accordance with some embodiments.

FIG. **25**F shows a representative radiating element following a meandering pattern in accordance with some embodiments.

FIG. **25**G shows a top view of a near-field antenna in accordance with some embodiments.

FIG. **25**H shows another top view of a near-field antenna in accordance with some embodiments.

FIG. **26** is a block diagram of a control system used for controlling operation of a near-field antenna in accordance with some embodiments.

FIG. **27** shows a radiation pattern generated by the near-field antenna with a reflector of FIG. **25**A.

FIGS. **28**A to **28**C show additional radiation patterns generated by the near-field antenna of FIG. **25**A.

FIGS. **29**A and **29**B show concentrations of energy radiated and absorbed by dipole antennas of a near-field antenna in accordance with some embodiments.

FIG. **30** is a flow diagram showing a method of wireless power transmission in accordance with some embodiments.

In accordance with common practice, the various features illustrated in the drawings may not be drawn to scale. Accordingly, the dimensions of the various features may be arbitrarily expanded or reduced for clarity. In addition, some of the drawings may not depict all of the components of a given system, method or device. Finally, like reference numerals may be used to denote like features throughout the specification and figures.

DESCRIPTION OF EMBODIMENTS

Reference will now be made in detail to embodiments, examples of which are illustrated in the accompanying drawings. In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the various described embodiments. However, it will be apparent to one of ordinary skill in the art that the various described embodiments may be practiced without these specific details. In other instances, well-known methods, procedures, components, circuits, and networks have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

FIG. **1**A is a block diagram of an RF wireless power transmission system in accordance with some embodiments. In some embodiments, the RF wireless power transmission system **150** includes a RF charging pad **100** (also referred to herein as a near-field (NF) charging pad **100** or RF charging pad **100**). In some embodiments, the RF charging pad **100** includes an RF power transmitter integrated circuit **160** (described in more detail below). In some embodiments, the RF charging pad **100** includes one or more communications components **204** (e.g., wireless communication components, such as WI-FI or BLUETOOTH radios), discussed in more detail below with reference to FIG. **2**A. In some embodiments, the RF charging pad **100** also connects to one or more power amplifier units **108-1**, . . . **108-*n*** to control operation of the one or more power amplifier units when they drive an external TX antenna array **210**. In some embodiments, RF power is controlled and modulated at the RF charging pad **100** via switch circuitry as to enable the RF wireless power transmission system to send RF power to one or more wireless receiving devices via the TX antenna array **210**. Example power amplifier units are discussed in further detail below with reference to FIG. **3**A.

In some embodiments, the communication component(s) **204** enable communication between the RF charging pad **100** and one or more communication networks. In some embodiments, the communication component(s) **204** are capable of data communications using any of a variety of custom or standard wireless protocols (e.g., IEEE 802.15.4, Wi-Fi, ZigBee, 6LoWPAN, Thread, Z-Wave, Bluetooth Smart, ISA100.11a, WirelessHART, MiWi, etc.) custom or standard wired protocols (e.g., Ethernet, HomePlug, etc.), and/or any other suitable communication protocol, including communication protocols not yet developed as of the filing date of this document.

FIG. **1**B is a block diagram of the RF power transmitter integrated circuit **160** (the "integrated circuit") in accordance with some embodiments. In some embodiments, the integrated circuit **160** includes a CPU subsystem **170**, an external device control interface, an RF subsection for DC to RF power conversion, and analog and digital control interfaces interconnected via an interconnection component, such as a bus or interconnection fabric block **171**. In some embodiments, the CPU subsystem **170** includes a microprocessor unit (CPU) **202** with related Read-Only-Memory (ROM) **172** for device program booting via a digital control interface, e.g. an I^2C port, to an external FLASH containing the CPU executable code to be loaded into the CPU Subsystem Random Access Memory (RAM) **174** (e.g., memory **206**, FIG. **2**A) or executed directly from FLASH. In some embodiments, the CPU subsystem **170** also includes an encryption module or block **176** to authenticate and secure communication exchanges with external devices, such as wireless power receivers that attempt to receive wirelessly delivered power from the RF charging pad **100**.

In some embodiments, executable instructions running on the CPU (such as those shown in the memory **206** in FIG. **2**A and described below) are used to manage operation of the RF charging pad **100** and to control external devices through a control interface, e.g., SPI control interface **175**, and the other analog and digital interfaces included in the RF power transmitter integrated circuit **160**. In some embodiments, the CPU subsystem also manages operation of the RF subsection of the RF power transmitter integrated circuit **160**, which includes an RF local oscillator (LO) **177** and an RF transmitter (TX) **178**. In some embodiments, the RF LO **177** is adjusted based on instructions from the CPU subsystem **170** and is thereby set to different desired frequencies of operation, while the RF TX converts, amplifies, modulates the RF output as desired to generate a viable RF power level.

In some embodiments, the RF power transmitter integrated circuit **160** provides the viable RF power level (e.g., via the RF TX **178**) to an optional beamforming integrated circuit (IC) **109**, which then provides phase-shifted signals to one or more power amplifiers **108**. In some embodiments, the beamforming IC **109** is used to ensure that power transmission signals sent using two or more antennas **210** (e.g., each antenna **210** may be associated with a different antenna zones **290** or may each belong to a single antenna zone **290**) to a particular wireless power receiver are transmitted with appropriate characteristics (e.g., phases) to ensure that power transmitted to the particular wireless power receiver is maximized (e.g., the power transmission signals arrive in phase at the particular wireless power receiver). In some embodiments, the beamforming IC **109** forms part of the RF power transmitter IC **160**.

In some embodiments, the RF power transmitter integrated circuit **160** provides the viable RF power level (e.g., via the RF TX **178**) directly to the one or more power amplifiers **108** and does not use the beamforming IC **109** (or bypasses the beamforming IC if phase-shifting is not required, such as when only a single antenna **210** is used to transmit power transmission signals to a wireless power receiver).

In some embodiments, the one or more power amplifiers **108** then provide RF signals to the antenna zones **290** for transmission to wireless power receivers that are authorized to receive wirelessly delivered power from the RF charging pad **100**. In some embodiments, each antenna zone **290** is coupled with a respective PA **108** (e.g., antenna zone **290-1** is coupled with PA **108-1** and antenna zone **290**-N is coupled with PA **108**-N). In some embodiments, multiple antenna zones are each coupled with a same set of PAs **108** (e.g., all PAs **108** are coupled with each antenna zone **290**). Various arrangements and couplings of PAs **108** to antenna zones **290** allow the RF charging pad **100** to sequentially or selectively activate different antenna zones in order to determine the most efficient antenna zone **290** to use for transmitting wireless power to a wireless power receiver (as explained in more detail below in reference to FIGS. **9**A-**9**B, **10**, and **11**A-**11**E). In some embodiments, the one or more power amplifiers **108** are also in communication with the CPU subsystem **170** to allow the CPU **202** to measure output power provided by the PAs **108** to the antenna zones of the RF charging pad **100**.

FIG. **1**B also shows that, in some embodiments, the antenna zones **290** of the RF charging pad **100** may include one or more antennas **210**A-N. In some embodiments, each antenna zones of the plurality of antenna zones includes one or more antennas **210** (e.g., antenna zone **290-1** includes one antenna **210**-A and antenna zones **290**-N includes multiple antennas **210**). In some embodiments, a number of antennas included in each of the antenna zones is dynamically defined based on various parameters, such as a location of a wireless power receiver on the RF charging pad **100**. In some embodiments, the antenna zones may include one or more of the meandering line antennas described in more detail below. In some embodiments, each antenna zone **290** may include antennas of different types (e.g., a meandering line antenna and a loop antenna), while in other embodiments each antenna zone **290** may include a single antenna of a same type (e.g., all antenna zones **290** include one meandering line antenna), while in still other embodiments, the antennas zones may include some antenna zones that include a single antenna of a same type and some antenna zones that include antennas of different types. Antenna zones are also described in further detail below.

In some embodiments, the RF charging pad **100** may also include a temperature monitoring circuit that is in communication with the CPU subsystem **170** to ensure that the RF charging pad **100** remains within an acceptable temperature range. For example, if a determination is made that the RF charging pad **100** has reached a threshold temperature, then operation of the RF charging pad **100** may be temporarily suspended until the RF charging pad **100** falls below the threshold temperature.

By including the components shown for RF power transmitter circuit **160** (FIG. **1**B) on a single chip, such integrated circuits are able to manage operations at the integrated circuits more efficiently and quickly (and with lower latency), thereby helping to improve user satisfaction with the charging pads that are managed by these integrated circuits. For example, the RF power transmitter circuit **160** is cheaper to construct, has a smaller physical footprint, and is simpler to install. Furthermore, and as explained in more detail below in reference to FIG. **2**A, the RF power transmitter circuit **160** may also include a secure element module **234** (e.g., included in the encryption block **176** shown in FIG. **1**B) that is used in conjunction with a secure element module **282** (FIG. **2**B) or a receiver **104** to ensure that only authorized receivers are able to receive wirelessly delivered power from the RF charging pad **100** (FIG. **1**B).

FIG. **1**C is a block diagram of a charging pad **294** in accordance with some embodiments. The charging pad **294** is an example of the charging pad **100** (FIG. **1**A), however, one or more components included in the charging pad **100** are not included in the charging pad **294** for ease of discussion and illustration.

The charging pad **294** includes an RF power transmitter integrated circuit **160**, one or more power amplifiers **108**, and a transmitter antenna array **290** having multiple antenna zones. Each of these components is described in detail above with reference to FIGS. **1**A and **1**B. Additionally, the charging pad **294** includes a switch **295**, positioned between the power amplifiers **108** and the antenna array **290**, having a plurality of switches **297**-A, **297**-B, . . . **297**-N. The switch **295** is configured to switchably connect one or more power amplifiers **108** with one or more antenna zones of the antenna array **290** in response to control signals provided by the RF power transmitter integrated circuit **160**.

To accomplish the above, each switch **297** is coupled with (e.g., provides a signal pathway to) a different antenna zone of the antenna array **290**. For example, switch **297**-A may be coupled with a first antenna zone **290-1** (FIG. **1**B) of the antenna array **290**, switch **297**-B may be coupled with a second antenna zone **290-2** of the antenna array **290**, and so on. Each of the plurality of switches **297**-A, **297**-B, . . . **297**-N, once closed, creates a unique pathway between a respective power amplifier **108** (or multiple power amplifiers **108**) and a respective antenna zone of the antenna array **290**. Each unique pathway through the switch **295** is used to selectively provide RF signals to specific antenna zones of the antenna array **290**. It is noted that two or more of the plurality of switches **297**-A, **297**-B, . . . **297**-N may be closed at the same time, thereby creating multiple unique pathways to the antenna array **290** that may be used simultaneously.

In some embodiments, the RF power transmitter integrated circuit **160** is coupled to the switch **295** and is configured to control operation of the plurality of switches **297**-A, **297**-B, . . . **297**-N (illustrated as a "control out" signal in FIGS. **1**A and **1**C). For example, the RF power transmitter integrated circuit **160** may close a first switch **297**-A while keeping the other switches open. In another example, the RF power transmitter integrated circuit **160** may close a first switch **297**-A and a second switch **297**-B, and keep the other switches open (various other combinations and configuration are possible). Moreover, the RF power transmitter integrated circuit **160** is coupled to the one or more power amplifiers **108** and is configured to generate a suitable RF signal (e.g., the "RF Out" signal) and provide the RF signal to the one or more power amplifiers **108**. The one or more power amplifiers **108**, in turn, are configured to provide the RF signal to one or more antenna zones of the antenna array **290** via the switch **295**, depending on which switches **297** in the switch **295** are closed by the RF power transmitter integrated circuit **160**.

To further illustrate, as described in some embodiments below, the charging pad is configured to transmit test power transmission signals and/or regular power transmission signals using different antenna zones, e.g., depending on a location of a receiver on the charging pad. Accordingly, when a particular antenna zone is selected for transmitting test signals or regular power signals, a control signal is sent to the switch **295** from the RF power transmitter integrated circuit **160** to cause at least one switch **297** to close. In doing so, an RF signal from at least one power amplifier **108** can be provided to the particular antenna zone using a unique pathway created by the now-closed at least one switch **297**.

In some embodiments, the switch **295** may be part of (e.g., internal to) the antenna array **290**. Alternatively, in some embodiments, the switch **295** is separate from the antenna array **290** (e.g., the switch **295** may be a distinct component, or may be part of another component, such as the power amplifier(s) **108**). It is noted that any switch design capable of accomplishing the above may be used, and the design of the switch **295** illustrated in FIG. **1**C is merely one example.

FIG. **2**A is a block diagram illustrating certain components of an RF charging pad **100** in accordance with some embodiments. In some embodiments, the RF charging pad **100** includes an RF power transmitter IC **160** (and the components included therein, such as those described above in reference to FIGS. **1**A-**1**B), memory **206** (which may be included as part of the RF power transmitter IC **160**, such as nonvolatile memory **206** that is part of the CPU subsystem **170**), and one or more communication buses **208** for interconnecting these components (sometimes called a chipset). In some embodiments, the RF charging pad **100** includes one or more sensor(s) **212** (discussed below). In some embodiments, the RF charging pad **100** includes one or more output devices such as one or more indicator lights, a sound card, a speaker, a small display for displaying textual information and error codes, etc. In some embodiments, the RF charging pad **100** includes a location detection device, such as a GPS (global positioning satellite) or other geolocation receiver, for determining the location of the RF charging pad **100**.

In some embodiments, the one or more sensor(s) **212** include one or more thermal radiation sensors, ambient temperature sensors, humidity sensors, IR sensors, occupancy sensors (e.g., RFID sensors), ambient light sensors, motion detectors, accelerometers, and/or gyroscopes.

The memory **206** includes high-speed random access memory, such as DRAM, SRAM, DDR SRAM, or other random access solid state memory devices; and, optionally, includes non-volatile memory, such as one or more magnetic disk storage devices, one or more optical disk storage devices, one or more flash memory devices, or one or more other non-volatile solid state storage devices. The memory **206**, or alternatively the non-volatile memory within memory **206**, includes a non-transitory computer-readable storage medium. In some embodiments, the memory **206**, or the non-transitory computer-readable storage medium of the memory **206**, stores the following programs, modules, and data structures, or a subset or superset thereof:

- Operating logic **216** including procedures for handling various basic system services and for performing hardware dependent tasks;
- Communication module **218** for coupling to and/or communicating with remote devices (e.g., remote sensors, transmitters, receivers, servers, mapping memories, etc.) in conjunction with wireless communication component(s) **204**;
- Sensor module **220** for obtaining and processing sensor data (e.g., in conjunction with sensor(s) **212**) to, for example, determine the presence, velocity, and/or positioning of object in the vicinity of the RF charging pad **100**;
- Power-wave generating module **222** for generating and transmitting power transmission signals (e.g., in conjunction with antenna zones **290** and the antennas **210** respectively included therein), including but not limited to, forming pocket(s) of energy at given locations. Power-wave generating module **222** may also be used to modify transmission characteristics used to transmit power transmission signals by individual antenna zones; and
- Database **224**, including but not limited to:
  - Sensor information **226** for storing and managing data received, detected, and/or transmitted by one or more sensors (e.g., sensors **212** and/or one or more remote sensors);
  - Device settings **228** for storing operational settings for the RF charging pad **100** and/or one or more remote devices;
  - Communication protocol information **230** for storing and managing protocol information for one or more protocols (e.g., custom or standard wireless protocols, such as ZigBee, Z-Wave, etc., and/or custom or standard wired protocols, such as Ethernet); and

Mapping data **232** for storing and managing mapping data (e.g., mapping one or more transmission fields);

secure element module **234** for determining whether a wireless power receiver is authorized to receive wirelessly delivered power from the RF charging pad **100**; and

an antenna zone selecting and tuning module **237** for coordinating a process of transmitting test power transmission signals with various antenna zones to determine which antenna zone or zones should be used to wirelessly deliver power to various wireless power receivers (as is explained in more detail below in reference to FIGS. **9A-9B**, **100**, and **11A-11E**).

Each of the above-identified elements (e.g., modules stored in memory **206** of the RF charging pad **100**) is optionally stored in one or more of the previously mentioned memory devices, and corresponds to a set of instructions for performing the function(s) described above. The above identified modules or programs (e.g., sets of instructions) need not be implemented as separate software programs, procedures, or modules, and thus various subsets of these modules are optionally combined or otherwise rearranged in various embodiments. In some embodiments, the memory **206**, optionally, stores a subset of the modules and data structures identified above.

FIG. **2B** is a block diagram illustrating a representative receiver device **104** (also sometimes called a receiver, power receiver, or wireless power receiver) in accordance with some embodiments. In some embodiments, the receiver device **104** includes one or more processing units (e.g., CPUs, ASICs, FPGAs, microprocessors, and the like) **252**, one or more communication components **254**, memory **256**, antenna(s) **260**, power harvesting circuitry **259**, and one or more communication buses **258** for interconnecting these components (sometimes called a chipset). In some embodiments, the receiver device **104** includes one or more sensor(s) **262** such as the one or sensors **212** described above with reference to FIG. **2A**. In some embodiments, the receiver device **104** includes an energy storage device **261** for storing energy harvested via the power harvesting circuitry **259**. In various embodiments, the energy storage device **261** includes one or more batteries, one or more capacitors, one or more inductors, and the like.

In some embodiments, the power harvesting circuitry **259** includes one or more rectifying circuits and/or one or more power converters. In some embodiments, the power harvesting circuitry **259** includes one or more components (e.g., a power converter) configured to convert energy from power waves and/or energy pockets to electrical energy (e.g., electricity). In some embodiments, the power harvesting circuitry **259** is further configured to supply power to a coupled electronic device, such as a laptop or phone. In some embodiments, supplying power to a coupled electronic device include translating electrical energy from an AC form to a DC form (e.g., usable by the electronic device).

In some embodiments, the antenna(s) **260** include one or more of the meandering line antennas that are described in further detail below.

In some embodiments, the receiver device **104** includes one or more output devices such as one or more indicator lights, a sound card, a speaker, a small display for displaying textual information and error codes, etc. In some embodiments, the receiver device **104** includes a location detection device, such as a GPS (global positioning satellite) or other geo-location receiver, for determining the location of the receiver device **103**.

In various embodiments, the one or more sensor(s) **262** include one or more thermal radiation sensors, ambient temperature sensors, humidity sensors, IR sensors, occupancy sensors (e.g., RFID sensors), ambient light sensors, motion detectors, accelerometers, and/or gyroscopes.

The communication component(s) **254** enable communication between the receiver **104** and one or more communication networks. In some embodiments, the communication component(s) **254** are capable of data communications using any of a variety of custom or standard wireless protocols (e.g., IEEE 802.15.4, Wi-Fi, ZigBee, 6LoWPAN, Thread, Z-Wave, Bluetooth Smart, ISA100.11a, WirelessHART, MiWi, etc.) custom or standard wired protocols (e.g., Ethernet, HomePlug, etc.), and/or any other suitable communication protocol, including communication protocols not yet developed as of the filing date of this document.

The communication component(s) **254** include, for example, hardware capable of data communications using any of a variety of custom or standard wireless protocols (e.g., IEEE 802.15.4, Wi-Fi, ZigBee, 6LoWPAN, Thread, Z-Wave, Bluetooth Smart, ISA100.11a, WirelessHART, MiWi, etc.) and/or any of a variety of custom or standard wired protocols (e.g., Ethernet, HomePlug, etc.), or any other suitable communication protocol, including communication protocols not yet developed as of the filing date of this document.

The memory **256** includes high-speed random access memory, such as DRAM, SRAM, DDR SRAM, or other random access solid state memory devices; and, optionally, includes non-volatile memory, such as one or more magnetic disk storage devices, one or more optical disk storage devices, one or more flash memory devices, or one or more other non-volatile solid state storage devices. The memory **256**, or alternatively the non-volatile memory within memory **256**, includes a non-transitory computer-readable storage medium. In some embodiments, the memory **256**, or the non-transitory computer-readable storage medium of the memory **256**, stores the following programs, modules, and data structures, or a subset or superset thereof:

Operating logic **266** including procedures for handling various basic system services and for performing hardware dependent tasks;

Communication module **268** for coupling to and/or communicating with remote devices (e.g., remote sensors, transmitters, receivers, servers, mapping memories, etc.) in conjunction with communication component(s) **254**;

Sensor module **270** for obtaining and processing sensor data (e.g., in conjunction with sensor(s) **262**) to, for example, determine the presence, velocity, and/or positioning of the receiver **103**, a RF charging pad **100**, or an object in the vicinity of the receiver **103**;

Wireless power-receiving module **272** for receiving (e.g., in conjunction with antenna(s) **260** and/or power harvesting circuitry **259**) energy from power waves and/or energy pockets; optionally converting (e.g., in conjunction with power harvesting circuitry **259**) the energy (e.g., to direct current); transferring the energy to a coupled electronic device; and optionally storing the energy (e.g., in conjunction with energy storage device **261**); and

Database **274**, including but not limited to:

Sensor information **276** for storing and managing data received, detected, and/or transmitted by one or more sensors (e.g., sensors **262** and/or one or more remote sensors);

Device settings **278** for storing operational settings for the receiver **103**, a coupled electronic device, and/or one or more remote devices; and

Communication protocol information **280** for storing and managing protocol information for one or more protocols (e.g., custom or standard wireless protocols, such as ZigBee, Z-Wave, etc., and/or custom or standard wired protocols, such as Ethernet); and

a secure element module **282** for providing identification information to the RF charging pad **100** (e.g., the RF charging pad **100** uses the identification information to determine if the wireless power receiver **104** is authorized to receive wirelessly delivered power).

Each of the above-identified elements (e.g., modules stored in memory **256** of the receiver **104**) is optionally stored in one or more of the previously mentioned memory devices, and corresponds to a set of instructions for performing the function(s) described above. The above identified modules or programs (e.g., sets of instructions) need not be implemented as separate software programs, procedures, or modules, and thus various subsets of these modules are optionally combined or otherwise rearranged in various embodiments. In some embodiments, the memory **256**, optionally, stores a subset of the modules and data structures identified above. Furthermore, the memory **256**, optionally, stores additional modules and data structures not described above, such as an identifying module for identifying a device type of a connected device (e.g., a device type for an electronic device that is coupled with the receiver **104**).

Turning now to FIGS. **3**A through **8**, embodiments of the RF charging pad **100** are shown that include a component for modifying impedance values (e.g., a load pick) at various antennas of the RF charging pad **100**, and descriptions of antennas that include a conductive line forming a meandering line pattern are also provided in reference to these figures.

As shown in FIG. **3**A, some embodiments include an RF charging pad **100** that includes a load pick **106** to allow for modifying impedance values at various antennas of the RF charging pad **100**. In some embodiments, the RF charging pad **100** includes one or more antenna elements that are each powered/fed by a respective power amplifier switch circuit **103** at a first end and a respective adaptive load terminal **102** at a second end (additional details and descriptions of the one or more antenna elements are provided below in reference to FIGS. **3**B-**3**C).

In some embodiments, the RF charging pad **100** also includes (or is in communication with) a central processing unit **110** (also referred to here as processor **110**). In some embodiments, the processor **110** is a component of a single integrated circuit that is responsible for managing operations of the RF charging pad **100**, such as the CPU **202** illustrated in FIG. **1**B and included as a component of the RF power transmitter integrated circuit **160**. In some embodiments, the processor **110** is configured to control RF signal frequencies and to control impedance values at each of the adaptive load terminals **102** (e.g., by communicating with the load pick or adaptive load **106**, which may be an application-specific integrated circuit (ASIC), or a variable resister, to generate various impedance values). In some embodiments, the load pick **106** is an electromechanical switch that is placed in either an open or shorted state.

In some embodiments, an electronic device (e.g., a device that includes a receiver **104** as an internally or externally connected component, such as a remote that is placed on top of a charging pad **100** that may be integrated within a housing of a streaming media device or a projector) and uses energy transferred from one or more RF antenna elements of the charging pad **100** to the receiver **104** to charge a battery and/or to directly power the electronic device.

In some embodiments, the RF charging pad **100** is configured with more than one input terminal for receiving power (from power amplifier (PA) **108**, FIG. **3**A) and more than one output or adaptive load terminal **102**. In some embodiments, the adaptive load terminals **102** at a particular zone of the RF charging pad **100** (e.g., a zone that includes antenna elements located underneath a position at which an electronic device (with an internally or externally connected RF receiver **104**) to be charged is placed on the charging pad) are optimized in order to maximize power received by the receiver **104**. For example, the CPU **110** upon receiving an indication that an electronic device with an internally or externally connected RF receiver **104** has been placed on the pad **100** in a particular zone **105** (the zone **105** includes a set of antenna elements) may adapt the set of antenna elements to maximize power transferred to the RF receiver **104**. Adapting the set of antenna elements may include the CPU **110** commanding load pick **106** to try various impedance values for adaptive load terminals **102** that are associated with the set of antenna elements. For example, the impedance value for a particular conductive line at an antenna element is given by the complex value of Z=A+jB (where A is the real part of the impedance value and B is the imaginary part, e.g., 0+j0, 1000+j0, 0+50j, or 25+j75, etc.), and the load pick adjusts the impedance value to maximize the amount of energy transferred from the set of antenna elements to the RF receiver **104**. In some embodiments, adapting the set of antenna elements also or alternatively includes the CPU **110** causing the set of antenna elements to transmit RF signals at various frequencies until a frequency is found at which a maximum amount of energy is transferred to the RF receiver **104**. In some embodiments, adjusting the impedance value and/or the frequencies at which the set of antenna elements transmits causes changes to the amount of energy transferred to the RF receiver **104**. In this way, the amount of energy transferred to the RF receiver **104** is maximized (e.g., to transfer at least 75% of the energy transmitted by antenna elements of the pad **100** to the receiver **104**, and in some embodiments, adjusting the impedance value and/frequencies may allow up to 98% of the energy transmitted to be received by the receiver **104**) may be received at any particular point on the pad **100** at which the RF receiver **104** might be placed.

In some embodiments, the input circuit that includes the power amplifier **108** can additionally include a device that can change frequencies of the input signal, or a device that can operate at multiple frequencies at the same time, such as an oscillator or a frequency modulator.

In some embodiments, the CPU **110** determines that a maximum amount of energy is being transferred to the RF receiver **104** when the amount of energy transferred to the RF receiver **104** crosses a predetermined threshold (e.g., 75% or more of transmitted energy is received, such as up to 98%) or by testing transmissions with a number of impedance and/or frequency values and then selecting the combination of impedance and frequency that results in maximum energy being transferred to the RF receiver **104** (as described in reference to the adaptation scheme below).

In some embodiments, an adaptation scheme is employed to adaptively adjust the impedance values and/or frequencies of the RF signal(s) emitted from the RF antenna(s) **120** of the charging pad **100**, in order to determine which combinations of frequency and impedance result in maximum energy transfer to the RF receiver **104**. For example, the processor **110** that is connected to the charging pad **100** tries different frequencies (i.e., in the allowed operating frequency range or ranges) at a given location of the RF charging pad **100** (e.g., a zone or area of the RF charging pad **100** that includes one or more RF antenna elements for transmitting RF signals, such as zone **105** of FIG. **3**A) to attempt to adaptively optimize for better performance. For example, a simple optimization either opens/disconnects or closes/shorts each load terminal to ground (in embodiments in which a relay is used to switch between these states), and may also cause RF antennas within the zone to transmit at various frequencies. In some embodiments, for each combination of relay state (open or shorted) and frequency, the energy transferred to the receiver **104** is monitored and compared to energy transferred when using other combinations. The combination that results in maximum energy transfer to the receiver **104** is selected and used to continue to transmitting the one or more RF signals to the receiver **104**. In some embodiments, the adaptation scheme described above is performed as a part of the methods described below in reference to FIGS. **9**A-**9**B, **10**, and **11**A-**11**E to help maximize an amount of energy transferred by the RF charging pad **100** to the receiver **104**.

As another example, if five frequencies in the ISM band are utilized by the pad **100** for transmitting radio frequency waves and the load pick **106** is an electromechanical relay for switching between open and shorted states, then employing the adaptation scheme would involve trying **10** combinations of frequencies and impedance values for each antenna element **120** or for a zone of antenna elements **120** and selecting the combination that results in best performance (i.e., results in most power received at receiver **104**, or most power transferred from the pad **100** to the RF receiver **104**).

The industrial, scientific, and medical radio bands (ISM bands) refers to a group of radio bands or parts of the radio spectrum that are internationally reserved for the use of radio frequency (RF) energy intended for scientific, medical and industrial requirements rather than for communications. In some embodiments, all ISM bands (e.g., 40 MHz, 900 MHz, 2.4 GHz, 5.8 GHz, 24 GHz, 60 GHz, 122 GHz, and 245 GHz) may be employed as part of the adaptation scheme. As one specific example, if the charging pad **100** is operating in the 5.8 GHz band, then employing the adaptation scheme would include transmitting RF signals and then adjusting the frequency at predetermined increments (e.g., 50 MHz increments, so frequencies of 5.75 GHz, 5.755 GHz, 5.76 GHz, and so on). In some embodiments, the predetermined increments may be 5, 10 15, 20, 50 MHz increments, or any other suitable increment.

In some embodiments, the antenna elements **120** of the pad **100** may be configured to operate in two distinct frequency bands, e.g., a first frequency band with a center frequency of 915 MHz and a second frequency band with a center frequency of 5.8 GHz. In these embodiments, employing the adaptation scheme may include transmitting RF signals and then adjusting the frequency at first predetermined increments until a first threshold value is reached for the first frequency band and then adjusting the frequency at second predetermined increments (which may or may not be the same as the first predetermined increments) until a second threshold value is reached for the second frequency band. For example, the antenna elements **120** may be configured to transmit at 902 MHz, 915 MHz, 928 MHZ (in the first frequency band) and then at 5.795 GHz, 5.8 GHz, and 5.805 GHz (in the second frequency band). Additional details regarding antenna elements that are capable of operating at multiple frequencies are provided below in reference to FIGS. **14**A-**14**D and **15**.

Turning now to FIGS. **3**B-**3**C, high-level block diagrams showing a portion of an RF charging pad are illustrated, in accordance with some embodiments.

FIG. **3**B shows a schematic of a single TX antenna **120** (which may be a part of an antenna zone that includes one or an array of such antennas **120**, all forming the charging pad **100** that is shown in FIG. **3**A). In some embodiments, the TX antenna **120** is also referred to as a TX antenna element **120**. In some circumstances, an RF receiving unit/antenna (RX) (or a device that includes the receiving unit **104** as an internally or externally connected component) is placed on top of a portion of the pad **100** that includes the TX antenna **120** (which includes a conductive line that forms a meandered line arrangement, as shown in FIG. **3**B).

In some embodiments, the receiver **104** has no direct contact to a metallic conductive line of the single TX antenna **120** and is just coupled (i.e. in near-field zone) to the TX antenna **120**.

In some embodiments, the TX antenna **120** has two or more terminals (or ports) that are labeled as **121** (which may be a respective one of the terminals **102** of FIG. **3**A) and **123** (which may be connected to a respective one of the PA switch circuits **103** of FIG. **3**A) in FIG. **3**B. In some embodiments, the source of power (from the power amplifier or PA) is connected to terminal **123** and an adaptive load (e.g., an electromechanical switch or ASIC) is connected to terminal **121**. In some embodiments, the adaptive load is formed generally as a complex impedance which may have both real and imaginary parts (i.e., a complex adaptive load can be formed using active devices (e.g., integrated circuits or chips made of transistors) or passive devices formed by inductors/capacitors and resistors). In some embodiments, the complex impedance is given by the formula Z=A+jB (e.g., 0+j0, 100+j0, 0+50j, and etc.), as discussed above.

In some embodiments, the receiver **104** may also be considered as a third terminal. To eliminate wasted energy, the receiver **104** should be configured to absorb a maximum amount (e.g., 75% or more, such as 98%) of the induced power that travels from terminal **123** and towards terminal **121**. In some embodiments, processor **110** is connected to the receiver **104** through a feedback loop (e.g., by exchanging messages using a short-range communication protocol, such by BLUETOOTH low energy (BLE) to exchange messages). In some alternative embodiments, the feedback loop from the receiver back to the CPU at the transmitter may utilize a same frequency band as the power transmission signals transmitted by the pad **100**, rather than using a separate communication protocol and/or a different frequency band.

In some embodiments, the feedback loop and messages exchanged may be used to indicate an amount of energy received or alternatively or additionally may indicate an increase or decrease in the amount of energy received as compared to previous measurements. In some embodiments, the processor **110** monitors the amount of energy received by the receiver **104** at certain points in time and controls/optimizes the adaptive load to maximize the power transferred from terminal **123** to terminal **121**. In some embodiments, monitoring the amount of energy transferred includes one or both of (i) receiving information from the receiver **104** (or a component of an electronic device in which the receiver **104** is located) that indicates an amount of energy received by the receiver **104** at a certain point in time and (ii) monitoring an amount of energy that remains in the conductive line at terminal **121** (instead of having been absorbed by the receiver **104**). In some embodiments, both of these monitoring techniques are utilized while, in other embodiments, one or the other of these monitoring techniques is utilized.

In some embodiments, the receiver **104** (i.e., an electronic device that includes the receiver **104** as an internally or externally connected component) may be placed anywhere on top of the charging pad **100** (i.e., partially or fully covering the conductive line that forms a meandered pattern on a respective antenna element **120**) and the processor **110** will continue to monitor the amount of energy transferred and make needed adjustments (e.g., to impedance and/or frequency) to maximize the energy transferred to the receiver **104**.

To help illustrate operation of the charging pad **100** and the antenna elements **120** included therein, the transmitting antenna element **120** shown in FIG. **3**B is divided into two sections: 1) section **125** starts at the terminal **123** of the antenna element **120** and extends to an edge of the receiver **104**; and 2) section **127** is formed by the rest of the transmitting antenna element **120** and the terminal **121**. The blocks are described in more detail below with respect to FIG. **3**C. It should be understood that sections **125** and **127** are functional representations used for illustrative purposes, and they are not intended to designate a specific implementation that partitions an antenna element into separate sections.

Turning now to FIG. **3**C, a block diagram of the TX antenna **120** is shown. In some embodiments, an effective impedance value ($Z_{effective}$), starting from a point that divides sections **125** and **127** and ending at the TX antenna **120**'s connection to the adaptive load **106** (e.g., terminal **121**) will change based on location of the receiver **104** on the TX antenna **120** and based on a selected load provided by adaptive load **106** at the terminal **121**. In some embodiments, the selected load is optimized by the adaptive load **106** (in conjunction with the processor **110**, FIG. **3**A) to tune $Z_{effective}$ in such a way that the energy transferred between terminal **123** and the receiver **104** reaches a maximum (e.g., 75% or more of energy transmitted by antenna elements of the pad **100** is received by the RF receiver **104**, such as 98%), while energy transfer may also stay at a minimum from terminal **123** to terminal **121** (e.g., less than 25% of energy transmitted by antenna elements of the pad **100** is not received by the RF receiver **104** and ends up reaching terminal **121** or ends up being reflected back, including as little as 2%).

In embodiments in which an electromechanical switch (e.g., a mechanical relay) is used to switch between open and shorted states, moving the switch from the open to the shorted state (e.g., shorted to a ground plane) for a particular antenna element **120** causes the impedance value, $Z_{effective}$, at a respective terminal **121** for that particular antenna element **120** to drop to a value close to 0 (alternatively, switching from the shorted to the open state causes the impedance value to jump close to a value close to infinity). In some embodiments, the frequency adaptation scheme discussed above in reference to FIG. **3**A is employed to test various combinations of impedance values and RF signal frequencies, in order to maximize energy transferred to an RF receiver (e.g., receiver **104**, FIGS. **3**A-**3**C). In some embodiments, an integrated circuit (IC or chip) may be used instead of an electromechanical switch as the adaptive load **106**. In such embodiments, the adaptive load **106** is configured to adjust the impedance value along a range of values, such as between 0 and infinity. In some embodiments, the IC may be formed by adaptive/reconfigurable RF active and/or passive elements (e.g., transistors and transmission lines) that are controlled by firmware of the IC (and/or firmware executing on the CPU **110** that controls operation of the IC). In some embodiments, the impedance produced by the IC, and controlled through firmware and based on information from the feedback loop (discussed above in reference to FIG. **3**A), may be changed to cover any load values selected from a Smith Chart (or the IC may be designed to produce certain loads covering a portion of values form the Smith Chart). In some embodiments, this IC is distinct from the RF power transmitter integrated circuit **160** (FIG. **1**B) that is used to manage overall operation of the pad **100**, and this other IC is also in communication with the RF power transmitter integrated circuit **160** to allow the circuit **160** to control adjustments to impedance values. A Smith Chart may be sampled and stored in a memory (e.g., as a lookup table) that is accessible by the processor **110**, and the processor **110** may perform lookups using the stored Smith Chart to determine various impedance values to test. For example, the integrated circuit may be configured to select a predetermined number of complex values (e.g., 5j to 10j, 100+0j, or 0+50j, etc.) for the impedance value to test in combination with various RF transmission frequencies, in order to locate a combination of values that optimizes energy transferred to the receiver **104** (examples of maximized energy transfer are discussed above).

In some other embodiments, a transmitter or charging pad with more than one antenna elements **120** of FIG. **1**B with one adaptive load **106** may be configured to operate in two or more distinct frequency bands respectively at the same time. For example, a first antenna element operates at a first frequency or frequency band, a second antenna element operates at a second frequency or frequency band, and a third antenna element operates at a third frequency or frequency band, and a fourth antenna element operates at a fourth frequency or frequency band, and the four frequency bands are distinct from each other. A transmitter with two or more antenna elements **120** therefore can be used as a multi-band transmitter.

FIG. **3**D is a block diagram of a simplified circuit that illustrates energy flow within sections of an antenna element that is transmitting an RF signal, in accordance with some embodiments. The references to part1 and part2 in FIG. **3**D refer to sections illustrated in FIGS. **3**B and **3**C, in particular, part1 corresponds to section **125** and part2 corresponds to section **127**.

As shown in FIG. **3**D, the effective impedance ($Z_{effective}$) for a transmitting antenna element **120** is formed by the portion of the conductive line that is after the receiver **104** (which, in some embodiments, forms a meandered line pattern as discussed in more detail below) and the adaptive load (labelled to as section **127** in FIGS. **3**B and **3**C). In some embodiments, by optimizing, the load $Z_{effective}$ will be tuned so the energy transferred from PA to the receiver **104** is maximized; and, the energy remaining in the conductive line by the time it reaches the adaptive load is minimized (as discussed above).

FIG. **4** is a schematic of an antenna element with two terminals, in accordance with some embodiments. As shown in FIG. **4**, an input or first terminal of the antenna element **120** (also described as terminal **123** in reference to FIGS. **3**B-**3**D above) is connected with a power amplifier **108** and an output or second terminal (also described as terminal **121** in reference to FIGS. **3**B-**3**D above) is connected with a load pick **106** that allows for configuring an adaptive load. Stated another way, in some embodiments, the antenna element **120** is fed by the power amplifier **108** from the first terminal and the antenna element **120** is also terminated at a second terminal at an adaptive load (for example, the mechanical relay that switches between shorted and open states).

In some embodiments, the charging pad **100** (FIG. **3**A) is made of single-layer or multi-layer copper antenna elements **120** with conductive lines that form a meandered line pattern. In some embodiments, each of these layers has a solid ground plane as one of its layers (e.g., a bottom layer). One example of a solid ground plane is shown and labelled for the transmitting antenna element shown in FIG. **4**.

In some embodiments, the RF charging pad **100** (and individual antenna elements **120** included therein) is embedded in a consumer electronic device, such as a projector, a laptop, or a digital media player (such as a networked streaming media player, e.g. a ROKU device, that is connected to a television for viewing streaming television shows and other content). For example, by embedding the RF charging pad **100** in a consumer electronic device, a user is able to simply place a peripheral device, such as a remote for a projector or a streaming media player (e.g., the remote for the projector or streaming media player includes a respective receiver **104**, such as the example structures for a receiver **104** shown in FIGS. **7**A-**7**D), on top of the projector or the streaming media player and the charging pad **100** included therein will be able to transmit energy to a receiver **104** that is internally or externally connected to the remote, which energy is then harvested by the receiver **104** for charging of the remote.

In some embodiments, the RF charging pad **100** may be included in a USB dongle as a standalone charging device on which a device to be charged is placed. In some embodiments, the antenna elements **120** may be placed near a top surface, side surfaces, and/or a bottom surface of the USB dongle, so that a device to be charged may be placed at various positions that contact the USB dongle (e.g., a headphone that is being charged might sit on top of, underneath, or hang over the USB dongle and would still be able to receive RF transmissions from the embedded RF charging pad **100**).

In some embodiments, the RF charging pad **100** is integrated into furniture, such as desks, chairs, countertops, etc., thus allowing users to easily charge their devices (e.g., devices that includes respective receivers **104** as internally or externally connected components) by simply placing them on top of a surface that includes an integrated RF charging pad **100**.

Turning now to FIG. **5**, a flowchart of a method **500** of charging an electronic device through radio frequency (RF) power transmission is provided. Initially, a transmitter is provided **502** that includes at least one RF antenna (e.g., antenna element **120**, FIGS. **3**B-**3**D and **4**) for transmitting one or more RF signals or waves, i.e., an antenna designed to and capable of transmitting RF electromagnetic waves. In some embodiments, an array of RF antenna elements **120** are arranged adjacent to one another in a single plane, in a stack, or in a combination of thereof, thus forming an RF charging pad **100**. In some embodiments, the RF antenna elements **120** each include an antenna input terminal (e.g., the first terminal **123** discussed above in reference to FIG. **4**) and an antenna output terminal (e.g., the second terminal **121** discussed above in reference to FIG. **4**).

In some embodiments, a receiver (e.g., receiver **104**, FIGS. **3**A-**3**D) is also provided **504**. The receiver also includes one or more RF antennas for receiving RF signals **310**. In some embodiments, the receiver includes at least one rectenna that converts **318** the one or more RF signals into usable power to charge a device that includes the receiver **104** as an internally or externally connected component. In use, the receiver **104** is placed **506** within a near-field radio frequency distance to the at least one antenna. For example, the receiver may be placed on top of the at least one RF antenna or on top of a surface that is adjacent to the at least one RF antenna, such as a surface of a charging pad **100**.

One or more RF signals are then transmitted **508** via at the least one RF antenna. The system is then monitored **512**/**514** to determine the amount of energy that is transferred via the one or more RF signals from the at least one antenna to a RF receiver (as is also discussed above). In some embodiments, this monitoring **512** occurs at the transmitter, while in other embodiments the monitoring **514** occurs at the receiver which sends data back to the transmitter via a back channel (e.g., over a wireless data connection using WIFI or BLUETOOTH). In some embodiments, the transmitter and the receiver exchange messages via the back channel, and these messages may indicate energy transmitted and/or received, in order to inform the adjustments made at step **516**.

In some embodiments, a characteristic of the transmitter is adaptively adjusted at step **516** to attempt to optimize the amount of energy that is transferred from the at least one RF antenna to the receiver. In some embodiments, this characteristic is a frequency of the one or more RF signals and/or an impedance of the transmitter. In some embodiments, the impedance of the transmitter is the impedance of the adjustable load. Also in some embodiments, the at least one processor is also configured to control the impedance of the adaptive load. Additional details and examples regarding impedance and frequency adjustments are provided above.

In some embodiments, the transmitter includes a power input configured to be electrically coupled to a power source, and at least one processor (e.g., processor **110**, FIGS. **3**A-**3**B) configured to control at least one electrical signal sent to the antenna. In some embodiments, the at least one processor is also configured to control the frequency of the at least one signal sent to the antenna.

In some embodiments, the transmitter further comprises a power amplifier electrically coupled between the power input and the antenna input terminal (e.g., PA **108**, FIGS. **3**A, **3**B, **3**D, and **4**). Some embodiments also include an adaptive load electrically coupled to the antenna output terminal (e.g., terminal **121**, FIGS. **3**A-**3**C and **4**). In some embodiments, the at least one processor dynamically adjusts the impedance of the adaptive load based on the monitored amount of energy that is transferred from the at least one antenna to the RF receiver. In some embodiments, the at least one processor simultaneously controls the frequency of the at least one signal sent to the antenna.

In some embodiments, each RF antenna of the transmitter includes: a conductive line forming a meandered line pattern, a first terminal (e.g., terminal **123**) at a first end of the conductive line for receiving current that flows through the conductive line at a frequency controlled by one or more processors, and a second terminal (e.g., terminal **121**), distinct from the first terminal, at a second end of the conductive line, the second terminal coupled to a component (e.g., adaptive load **106**) controlled by the one or more processors and that allows for modifying an impedance value of the conductive line. In some embodiments, the conductive line is disposed on or within a first antenna layer of a multi-layered substrate. Also in some embodiments, a second antenna is disposed on or within a second antenna layer of the multi-layered substrate. Finally, some embodiments also provide a ground plane disposed on or within a ground plane layer of the multi-layered substrate.

In some embodiments, the method described above in reference to FIG. **5** is performed in conjunction with the methods described below in reference to FIGS. **9**A-**9**B, **10**, and **11**A-**11**E. For example, the operations of modifying/adjusting impedance values are performed after determining which antenna zones (the "determined antenna zones") to use for transmitting wireless power to a receiver, and then impedance values at the determined antenna zones are adjusted to ensure that a maximum amount of power is transferred wirelessly to the receiver by antennas within the determined antenna zones.

FIGS. **6**A-**6**E are schematics showing various configurations for individual antenna elements within an RF charging pad, in accordance with some embodiments. As shown in FIGS. **6**A-**6**E, an RF charging pad **100** (FIG. **3**A) may include antenna elements **120** that are made using different structures.

For example, FIGS. **6**A-**6**B show examples of structures for an antenna element **120** that includes multiple layers that each include conductive lines formed into meandered line patterns. The conductive lines at each respective layer may have the same (FIG. **6**B) or different (FIG. **6**A) widths (or lengths, or trace gauges, or patterns, spaces between each trace, etc.) relative to other conductive lines within a multi-layer antenna element **120**. In some embodiments, the meandered line patterns may be designed with variable lengths and/or widths at different locations of the pad **100** (or an individual antenna element **120**), and the meandered line patterns may be printed on more than one substrate of an individual antenna element **120** or of the pad **100**. These configurations of meandered line patterns allow for more degrees of freedom and, therefore, more complex antenna structures may be built that allow for wider operating bandwidths and/or coupling ranges of individual antenna elements **120** and the RF charging pad **100**.

Additional example structures are provided in FIGS. **6**C-**6**E: FIG. **6**C shows an example of a structure for an antenna element **120** that includes multiple layers of conductive lines forming meandered line patterns that also have sliding coverage (in some embodiments, respective meandered line patterns may be placed in different substrates with just a portion of a first meandered line pattern of a respective substrate overlapping the a second meandered line pattern of a different substrate (i.e., sliding coverage), and this configuration helps to extend coverage throughout width of the antenna structure); FIG. **6**D shows an example of a structure for an antenna element **120** that includes a conductive line having different lengths at each turn within the meandered line pattern (in some embodiments, using different lengths at each turn helps to extend coupling range of the antenna element **120** and/or helps add to the operating bandwidth of the RF charging pad **100**); and FIG. **6**E shows an example of a structure for an antenna element **120** that includes a conductive line that forms two adjacent meandered line patterns (in some embodiments, having a conductive line that forms two adjacent meandered line patterns helps to extend width of the antenna element **120**). All of these examples are non-limiting and any number of combinations and multi-layered structures are possible using the example structures described above.

FIGS. **7**A-**7**D are schematics of an antenna element for an RF receiver, in accordance with some embodiments. In particular FIGS. **7**A-**7**D show examples of structures for RF receivers (e.g., receiver **104**, FIGS. **3**A-**3**D and **4**), including: (i) a receiver with a conductive line that forms meandered line patterns (the conductive line may or may not be backed by solid ground plane or reflector), as shown in FIGS. **7**A (single-polarity receiver) and **7**B (dual-polarity receiver). FIGS. **7**C-**7**D show additional examples of structures for an RF receiver with dual-polarity and a conductive line that forms a meandered line pattern. Each of the structures shown in FIGS. **7**A-**7**D may be used to provide different coupling ranges, coupling orientations, and/or bandwidth for a respective RF receiver. As a non-limiting example, when the antenna element shown in FIG. **7**A is used in a receiver, very small receivers may be designed/built that only couple to the pad **100** in one direction. As another non-limiting example, when the antenna elements shown in FIGS. **7**B-**7**D are used in a receiver, the receiver is then able to couple to the pad **100** in any orientation.

Other examples and descriptions of meandered line patterns for antenna elements are provided below. FIG. **8** is a schematic of an RF charging pad with a plurality of transmitting antenna elements (unit cells) that form a larger RF charging/transmitting pad, in accordance with some embodiments. In some embodiments, the RF charging pad **100** is formed as an array of adjacent antenna elements **120** (the distance between cells may be optimized for the best coverage). In some embodiments, when a receiver is placed in an area/gap that is between adjacent antenna elements **120**, attempts to optimize energy transfer (e.g., in accordance with the adaptation scheme discussed above in reference to FIG. **3**A) may not result in increased energy transfer above an acceptable threshold level (e.g., 75% or more). As such, in these circumstances, adjacent antenna elements may both be configured to transmit RF waves at full power at the same time to transfer additional energy to a receiver that is placed on a surface of the RF charging pad, and at a location that is between adjacent antenna elements **120**.

As one possible configuration in accordance with some embodiments, port (or terminal) group #1 (FIG. **8**) supplies power, port (or terminal) groups #2 and #3 provide adaptive loads (e.g., an electromechanical relay moving between short-circuit and open-circuit states). As another example of a suitable configuration, port (or terminal) groups #1, #2 and #3 may also be used to supply power via a power amplifier to the charging pad **100** (at the same time or with one group at a time being switched when necessary).

In some embodiments, each transmitting antenna element **120** of the RF charging pad **100** forms a separate antenna zone which is controlled by a feeding (PA) terminal and one or more terminals to support adaptive load(s), as explained in detail above. In some embodiments, feedback from the receiver helps determine the antenna zone on top of which the receiver is placed, and this determination activates that zone (e.g., using the switch **295**, FIG. **1**C). In circumstances in which the receiver is placed between two or more zones (e.g., at an area/gap that is between adjacent antenna elements **120**), additional adjacent zones might be activated to ensure sufficient transfer of energy to the receiver. Additional details regarding determining zones to use for transmitting wireless power to the receiver are provided below in reference to FIGS. **9**A-**9**B, **10**, and **11**A-**11**E.

FIGS. **9**A-**9**B are flow diagrams showing a method **900** of selectively activating one or more antenna zones (e.g., activating the antennas associated therewith) in a near-field charging pad, in accordance with some embodiments. Operations of the method **900** are performed by a near-field charging pad (e.g. RF charging pad **100**, FIGS. **1**B and **2**A) or by one or more components thereof (e.g., those described above with reference to FIGS. **1**A-**1**B and **2**A). In some embodiments, the method **900** corresponds to instructions stored in a computer memory or computer-readable storage medium (e.g., memory **206** of the RF charging pad **100**, FIG. **2**A).

The near-field charging pad includes one or more processors (e.g., CPU **202**, FIG. **1**B), a wireless communication component (e.g., communication component(s) **204**, FIGS. **1**A and **2**A), and a plurality of antenna zones (e.g., antenna zones **290-1** and **290**-N, FIG. **1**B) that each respectively include at least one antenna element (e.g., one of antennas **210**, which may be one of the antennas **120** described in reference to FIGS. **3**A-**6**E) (**902**). In some embodiments, the near-field charging pad includes distinct antennas (or unit cells including antennas, also referred to herein as antenna elements) that are each included in respective antenna zones. For example, as shown in FIG. **1**B, an antenna zone **290-1** includes an antenna **210**-A. In another example, as is also shown in FIG. **1**B, an antenna zone **290**-N includes multiple antennas. The antenna zones may also be referred to as antenna groups, such that the near-field charging pad includes a plurality of antenna zones or groups, and each respective zone/group includes at least one of the distinct antenna elements (e.g., at least one antenna **210**). It should be noted that an antenna zone can include any number of antennas, and that the numbers of antennas associated with a particular antenna zone may be modified or adjusted (e.g., the CPU subsystem **170** of RF power transmitter integrated circuit **160** responsible for managing operations of the near-field charging pad **100** dynamically defines each antenna zone at various points in time, as is discussed in more detail below). In some embodiments, each antenna zone includes a same number of antennas.

In some embodiments, the one or more processors are a component of a single integrated circuit (e.g., RF power transmitter integrated circuit **160**, FIG. **1**B) that is used to control operation of the near-field charging pad. In some embodiments, the one or more processors and/or the wireless communication component of the near-field charging pad is/are external to the near-field charging pad, such as one or more processors of a device in which the near-field charging pad is embedded. In some embodiments, the wireless communication component is a radio transceiver (e.g., a BLUETOOTH radio, WI-FI radio, or the like for exchanging communication signals with wireless power receivers).

In some embodiments, the method includes establishing (**904**) one or more device detection thresholds during a calibration process for the near-field charging pad. In some instances, the calibration process is performed after manufacturing the near-field charging pad and includes placing devices of various types (e.g., smartphones, tablets, laptops, connected devices, etc.) on the near-field charging pad and then measuring a minimum amount of reflected power detected at an antenna zone while transmitting test power transmission signals to the devices of various types. In some instances, a first device-specific threshold is established at a value corresponding to 5% or less of the minimum amount of reflected power. In some embodiments, a second device-specific threshold is also established so that if no one antenna zone is able to satisfy the first threshold (e.g., because the wireless power receiver is located at a border between antenna zones), then the second, higher threshold may be used to locate more than one antenna zone to use for transmitting power to the wireless power receiver (as discussed in more detail below). In some embodiments, multiple first and second device-specific detection thresholds are established for each type of device of the various types, and these multiple first and second device-specific detection thresholds may be stored in a memory associated with the RF power transmitter integrated circuit **160** (e.g., memory **206**, FIG. **2**A).

The method **900** also includes detecting (**906**), via the wireless communication component, that a wireless power receiver is within a threshold distance of the near-field charging pad. In some instances, the detecting may occur after the near-field charging pad is turned on (e.g., powered up). In these instances, the near-field charging pad scans an area around the near-field charging pad (e.g., to scan for wireless power receivers that are located within the threshold distance, e.g., within 1-1.5 meters, away from the NF charging pad **100**) to determine whether any wireless power receivers are within the threshold distance of the NF charging pad **100**. The near-field charging pad may use the wireless communication component (e.g., communication component(s) **204**, FIG. **2**A, such as a Bluetooth radio) to conduct the scanning for signals broadcasted by wireless communication components associated with wireless power receivers (e.g., communication component **254**, FIG. **2**B). In some embodiments, the device detection threshold is selected (from among the multiple first and second device detection threshold discussed above) by the one or more processors after detecting the wireless power receiver within the threshold distance of the near-field charging pad. For example, a wireless communication component of the wireless power receiver is used to provide information to the near-field charging pad that identifies the type of device, such as a BLUETOOTH or BLUETOOTH low energy advertisement signal that includes this information. In some embodiments, to save energy and prolong life of the near-field charging pad and its components, no wireless power is transmitted (and the device detection and antenna selection algorithms discussion herein are not initiated) until a wireless power receiver is detected within the threshold distance of the near-field charging pad.

In some embodiments, the detecting **906** also includes performing an authorization handshake (e.g., using the secure element modules **234** and **282**, FIGS. **2**A and **2**B) to ensure that the wireless power receiver is authorized to receive wirelessly delivered power from the near-field charging pad and the method only proceeds to operation **908** if it is determined that the wireless power receiver is so authorized. In this way, the near-field charging pad ensures that only authorized wireless power receivers are able to receive wirelessly delivered power and that no device is able to leech power that is transmitted by the near-field charging pad.

The method **900** further includes, in response to detecting that the wireless power receiver is within the threshold distance of the near-field charging pad, determining (**912**) whether the wireless power receiver has been placed on the near-field charging pad. In some embodiments, this is accomplished by transmitting (**908**) test power transmission signals using each of the plurality of antenna zones and monitoring (**910**) an amount of reflected power at the near-field charging pad while transmitting the test power transmission signals.

In some embodiments, if the amount of reflected power does not satisfy the device detection threshold (e.g., the amount of reflected power is greater than 20% of power transmitted with the test power transmission signals), then a determination is made that the wireless power receiver has not been placed on the surface of the near-field charging pad (**912**—No). In accordance with this determination, the near-field charging pad continues to transmit test power transmission signals using each of the plurality of antenna zones at step **914** (i.e., proceed to step **908**). In some embodiments, the operations at **908** and **910** are performed until it is determined that the device detection threshold has been satisfied.

In some embodiments, the amount of reflected power is measured at each antenna zone of the plurality of antenna zones (e.g., each antenna zone may be associated with a respective ADC/DAC/Power Detector, such as the one shown in FIG. **1**B) while, in other embodiments, the amount of reflected power may be measured using a single component of the RF power transmitter integrated circuit **160** (e.g., the ADC/DAC/Power Detector). When the amount of reflected power satisfies the device detection threshold (**912**—Yes), the wireless power receiver is determined to have been placed on the near-field charging pad. For example, the amount of reflected power may satisfy the device detection threshold when the amount of reflected power is 20% or less than amount of power transmitted with the test power transmission signals. Such a result indicates that a sufficient amount of the power transmitted with the test power transmission signals was absorbed/captured by the wireless power receiver.

In some embodiments, other types of sensors (e.g., sensors **212**, FIG. **2**A) are included in or in communication with the near-field charging pad to help determine when the wireless power receiver has been placed on the near-field charging pad. For example, in some embodiments, one or more optical sensors (e.g., when light is blocked from a part of the pad, then this may provide an indication that the wireless power receiver has been placed on the pad), one or more vibration sensors (e.g., when a vibration is detected at the pad, then this may provide an indication that the wireless power receiver has been placed on the pad), one or more strain gauges (e.g., when a strain level at a surface of the pad increases, this may provide an indication that the wireless power receiver has been placed on the surface), one or more thermal sensors (e.g., when a temperature at a surface of the pad increases, this may provide an indication that the wireless power receiver has been placed on the surface), and/or one or more weighing sensors (e.g., when an amount of weight measured on the surface of the pad increases, then this may provide an indication that the wireless power receiver has been placed on the surface) are utilized to help make this determination.

In some embodiments, before transmitting the test power transmission signals, the method includes determining that the wireless power receiver is authorized to receive wirelessly delivered power from the near-field charging pad. For example, as shown in FIGS. **2**A-**2**B, the wireless power receiver **104** and the near-field charging pad **100** may include secure element modules **282** and **234**, respectively, which are used to perform this authorization process, thereby ensuring that only authorized receivers are able to receive wirelessly delivered power from the near-field charging pad.

The method **900** further includes, in accordance with determining that the wireless power receiver has been placed on the near-field charging pad, selectively transmitting (**916**), by respective antenna elements included in the plurality of antenna zones, respective test power transmission signals with a first set of transmission characteristics. In some embodiments, the selectively or sequentially transmitting is performed using each antenna zone of the plurality of antenna zones (**918**). Selectively or sequentially transmitting refers to a process of selectively activating antenna zones one at a time to cause one or more antennas associated with individual antenna zones to transmit test power transmission signals (e.g., the RF power transmitter integrated circuit **160** provides one or more control signals to the switch **295** to selectively activate different antenna zones).

Referring now to FIG. **9**B, the method **900** further includes determining (**920**) whether a particular power-delivery parameter associated with transmission of a respective test power transmission signal (during the sequential or selective transmission operation at **916** and/or **918**) by at least one particular antenna zone of the plurality of antenna zones satisfies power-delivery criteria (e.g., whether the particular power-delivery parameter indicates that more than a threshold amount of power is transferred to the wireless power receiver by the at least one particular antenna zone). In some embodiments, each respective power-delivery parameter corresponds to an amount of power received by the wireless power receiver based on transmission of a respective test power transmission signal by a respective antenna group of the plurality of antenna groups.

Upon determining, by the one or more processors, that the particular power-delivery parameter satisfies the power-delivery criteria (**920**—Yes), the method further includes transmitting (**922**) a plurality of additional power transmission signals to the wireless power receiver using the at least one particular antenna zone, where each additional power transmission signal of the plurality is transmitted with a second set of transmission characteristics, distinct from the first set. In some embodiments, the second set of transmission characteristics is determined by adjusting at least one characteristic in the first set of transmission characteristics to increase an amount of power that is transferred by the particular antenna group to the wireless power receiver. Moreover, in some embodiments, the at least one adjusted characteristic is a frequency or impedance value (and the frequency and impedance value may be adjusted using the adaptation scheme discussed above).

The test power transmission signals discussed above are used to help determine which antenna zones to use for delivering wireless power to the wireless power receiver. In some embodiments, these test power transmission signals are not used by the wireless power receiver to provide power or charge to the wireless power receiver, or a device associated therewith. Instead, the plurality of additional power transmission signals is used to provide power or charge to the wireless power receiver. In this way, the near-field charging pad is able to preserve resources during a device detection stage (e.g., while transmitting the test power transmission signals) until a suitable antenna zone is located for transmitting the plurality of additional power transmission signals. As such, the method **900** is able to locate a position of the wireless power receiver using test signals (i.e., the test power transmission signals with the first set of transmission characteristics) and then transmit using antenna from an antenna zone that is best-suited to provide power transmission signals given the position of the wireless power receiver on the near-field charging pad. As discussed in more detail below with reference to FIG. **10**, this process may include a coarse search for antenna zones (e.g., the coarse search may include the operations **908**-**918**) and a finer search for antenna zones (e.g., the finer search may include operations **920**-**934**).

In some embodiments, a power control process (FIG. **11**E) is also used to help optimize a level of power delivered to the wireless power receiver using the selected antenna zones (e.g., power control may be performed after operations **922**, **930**, or **934** to tune transmission of wireless power using the antenna zones that were selected during the method **900**). As a part of the power control process, the near-field charging pad may, while transmitting the additional plurality of power transmission signals, adjust at least one characteristic in the second set of transmission characteristics based on information, received from the wireless power receiver, which is used to determine a level of power that is wirelessly delivered to the wireless power receiver by the near-field charging pad.

Returning back to operation **920**, in response to determining that none of the power-delivery parameters associated with transmission of the test power transmission signals during the sequential or selective transmission operation(s) at **916** (and optionally **918**) satisfy the power-delivery criteria (**920**—No), the method **900** further includes selecting (**924**) two or more antenna zones (also referred to interchangeably herein as two+ antenna zones) based on their associated respective power-delivery parameters. This may arise when the wireless power receiver is not centered over any particular antenna zone (e.g., the receiver may be over more than one antenna zone). For example, the two or more antenna zones that transferred the highest amount of power to the wireless power receiver during the sequential or selective transmission operation at **916** (and optionally **918**) based on their respective power-delivery parameters are selected at operation **924**. In this way, in some embodiments, a finer search for the most efficient antenna zone is started by selecting the two or more antenna zones that most efficiently transmitted power to the wireless power receiver during the operations at **916**/**918** based on their respective association with power-delivery parameters that is higher than the power-delivery parameters for other antenna zones. In these embodiments, a respective power-delivery parameter may be monitored (in conjunction with operations **916**/**918**) for each antenna zone and these power-delivery parameters are then compared to determine which of the plurality of antenna zones to select as the two or more antenna zones to use for transmission of wireless power.

After selecting the two or more antenna zones, the method further includes: (i) updating the test power transmission signals by modifying at least one characteristic of the test power transmission signals (e.g., frequency, impedance, amplitude, phase, gain, etc.), based on the previous transmissions (e.g., based on feedback received from the wireless power receiver regarding a level of power receive by the wireless power receiver or based on an amount of reflected power measured at each antenna group after the transmission), and (ii) transmitting (**926**) the updated test power transmission signals using each of the two or more antenna zones (e.g., the RF power transmitter integrated circuit **160** may provide one or more control signals to the switch **295** to activate the two or more antenna zones).

The method **900** further includes determining (**928**) whether a particular power-delivery parameter associated with transmission of an updated respective test power transmission signal by a zone of the two or more antenna zones satisfies power-delivery criteria. In response to determining that the particular power-delivery parameter associated with transmission of the updated respective test power transmission signal by the zone of the two or more antenna zones satisfies the power-delivery criteria (**928**—Yes), the method **900** further includes transmitting (**930**) a plurality of additional power transmission signals to the wireless power receiver using the zone of the two or more antenna zones, where each additional power transmission signal of the plurality is transmitted with a second set of transmission characteristics, distinct from the first set (e.g., the RF power transmitter integrated circuit **160** may provide a control signal to the switch **295**). The plurality of additional power transmission signals is used to wirelessly deliver power to the wireless power receiver (or an electronic device coupled with the wireless power receiver).

In some embodiments, the determination that the particular power-delivery parameter satisfies the power-delivery criteria at operations **920** and **928** may include determining that respective power-delivery parameters (associated with the at least one particular zone and/or the zone of the two or more antenna zones) indicates that a first threshold amount of power is transferred to the wireless power receiver. If such a determination is made at operation **928**, this indicates that the zone is the only antenna zone of the two or more antenna zones having a respective power-delivery parameter that indicates that the first threshold amount of power is transferred to the wireless power receiver by the zone in conjunction with operation **926**.

In some embodiments, the first threshold amount of power corresponds to an amount of power received by the wireless power receiver (in some circumstances, the first threshold amount of power could alternatively correspond to an amount of reflected power detected at the near-field charging pad). As discussed above, in some embodiments, a calibration process is performed after manufacturing the near-field charging pad and includes placing devices of various types (e.g., smartphones, tablets, laptops, connected devices, etc., that are each coupled with wireless power receivers) on the near-field charging pad and then measuring a maximum amount of power received at the receiver (or device coupled thereto) after transmission of the test signal by an antenna group to the devices of various types. In some instances, the first threshold is established at a value corresponding to a percentage of the maximum amount of received power (e.g., approximately 85% or more of power transmitted by a particular antenna zone is received by the receiver).

As explained above, during embodiments of the calibration process, a second threshold is also established so that if no one antenna zone is able to satisfy the first threshold (e.g., because the wireless power receiver may be located at a border between antenna groups) then the second threshold may be utilized to locate more than one antenna zone to transmit wireless power to the wireless power receiver (as discussed below). This second threshold may be another percentage of the maximum amount of reflected power that is measured during the calibration process (e.g., 65%). In some embodiments, the first and second thresholds are determined as respective device-specific first and second thresholds for each of the devices undergoing the calibration process.

In some embodiments, the method **900** includes determining (**928**—No) that (i) no antenna zone of the two or more antenna zones is transferring the first threshold amount of power to the wireless power receiver and (ii) an additional power-delivery parameter associated with an additional antenna zone of the two or more antenna zones satisfies the power-delivery criteria. For example, a respective power-delivery parameter indicates that a first amount of power transferred to the wireless power receiver by the zone of the two or more zones is above a second threshold amount of power and below the first threshold amount of power, and the additional power-delivery parameter also indicates that a second amount of power transferred to the wireless power receiver by the additional antenna zone is above the second threshold amount of power and below the first threshold amount of power. In other words, if no antenna zone of the two or more antenna zones is able to transfer enough power to the wireless power receiver to satisfy the first threshold amount of power, then the method proceeds to determine whether two of the antenna groups transferred enough power to the wireless power receiver to satisfy a second, lower threshold amount of power. For example, the wireless power receiver may be located at a border between two antenna groups, so no one antenna group is able to satisfy the first threshold, but these two antenna groups may be able to each individually satisfy the second threshold amount of power.

Upon determining, by the one or more processors of the near-field charging pad, that the power-delivery parameters associated with transmission of the updated test power transmission signals by the two or more antennas zones satisfy the power-delivery criteria (**932**—Yes), the method further includes transmitting (**934**) a plurality of additional power transmission signals to the wireless power receiver using the two or more antenna zones. Such a situation may arise when the wireless power receiver is placed between two adjacent antenna zones. In some embodiments, the two or more antenna zones each simultaneously transmit the additional plurality of power transmission signals to provide power to the wireless power receiver.

As is also shown in FIG. **9**B, if the two or more zones do not have power-delivery parameters that satisfy the power-delivery criteria (**932**—No), then the method **900** returns to operation **906** to start searching for the receiver (or a different receiver again), as no antenna zones were located that could efficiently transfer wireless power to the receiver. In some embodiments, the method **900** may alternatively return to operation **924** to begin transmitting test power transmission signals with different characteristics to determine if those characteristics are able to then allow the two or more antenna zones to deliver enough wireless power to the receiver to satisfy the power-delivery criteria. In some embodiments, the method **900** returns to operation **924** a predetermined number of times (e.g., 2) and, if the two or more zones still do not have power-delivery parameters that satisfy the power-delivery criteria, then the method at that point returns to operation **906** to begin searching for new receivers.

In some embodiments, after the method **900** successfully locates antenna zones to use for wirelessly delivering power to the receiver (e.g., at operations **922**, **930**, and **934**) then the method **900** returns to operation **906** to being search for new receivers. The near-field charging pad, in some embodiments, is capable of simultaneously delivering wireless power to multiple receivers at any particular point in time and, therefore, iterating through the method **900** again allows the near-field charging pad to appropriately determine which antenna zones to use for transmission of wireless power to each of these multiple receivers.

In some embodiments, information used to determine respective power-delivery parameters for each of the antenna zones of the near-field charging pad is provided to the near-field charging pad by the wireless power receiver via the wireless communication component of the near-field charging pad (e.g., the receiver transmits information that is used to determine an amount of power received by the receiver from the test power transmission signals discussed above). In some embodiments, this information is sent via a connection between the wireless communication component of the near-field charging pad and the wireless power receiver, and the connection is established upon determining that the wireless power receiver has been placed on the near-field charging pad.

Additionally, in some embodiments, the near-field charging pad dynamically creates or defines antenna zones. For example, with reference to FIG. **1**B, the near-field charging pad may define a first antenna zone **290-1** to include a single antenna **210**-A and may define another antenna zone **290**-N to include more than one antenna **210**. In some embodiments, at various phases of the method **900** discussed above, antenna zones may be redefined. For example, in accordance with the determination that the two or more antenna zones do not have power-delivery parameters that satisfy the power-delivery criteria (**932**—No), the near-field charging pad may redefine the antenna zones to each include multiple antennas (instead of having each antenna zone include a single antenna). In this way, the method **900** is able to dynamically define antenna zones to help ensure that an appropriate antenna zone is located that may be used to transmit wireless power to a receiver that has been placed on the near-field charging pad.

FIG. **10** is an overview showing a process **1000** of selectively activating one or more antenna groups in a near-field charging pad, in accordance with some embodiments. Some of the operations in process **1000** correspond to or supplement the operations describe above in reference to method **900** of FIGS. **9**A-**9**B. As shown in FIG. **10**, the process **1000** begins with a near-field charging pad (e.g., RF charging pad **100**, FIGS. **1**A-**1**B and **2**A) detecting (**1002**) a wireless power receiver (e.g., wireless power receiver **104**, FIG. **12**B) in range and subsequently on the near-field charging pad (operation **1002** corresponds to operations **906** to **912**—Yes in FIG. **9**A). The process **1000** further includes performing (**1004**) a coarse search, performing (**1006**) a fine search, and executing (**1008**) a power control routine. Each step in the process **1000** is described in further detail below with reference to FIGS. **11**A-**11**E. It should be noted that the process **1000**, in some embodiments, begins with the near-field charging pad detecting (**1002**) a wireless power receiver on the near-field charging pad and subsequently in range of the near-field charging pad.

FIG. **11**A is a flowchart detailing a process **1002** for detecting a wireless power receiver in range and subsequently on the near-field charging pad (or in some embodiments, on the near-field charging pad and subsequently in range of the near-field charging pad). The process **1002** includes enabling the near-field charging pad (**1102**), i.e., powering on the near-field charging pad. Thereafter, the near-field charging pad scans (**1104**) for wireless power receivers and detects (**1106**) a wireless power receiver in range based, at least in part, on a received signal strength indicator (RSSI). To obtain the RSSI, the near-field charging pad may use a wireless communication component (e.g., communication component(s) **204**, FIG. **2**A, such as a Bluetooth radio) to scan for signals broadcasted by wireless communication components associated with wireless power receivers (e.g., a Bluetooth advertisement signal). Detecting a wireless power receiver in range of the near-field charging pad is discussed in further detail above with reference to operation **906** of the method **900**.

Next, the near-field charging pad detects (**1108**) a wireless power receiver on the near-field charging pad. In some embodiments, the near-field charging pad establishes that the wireless power receiver is on the near-field charging pad using the processes discussed above in reference to operations **908-914** until it is determined that the wireless power receiver has been placed on the near-field charging pad. In some embodiments, operation (**1108**) occurs before operation (**1102**).

Continuing, the near-field charging pad establishes (**1110**) a communication channel with the wireless power receiver in response to detecting the wireless power receiver on the near-field charging pad.

Turning now to FIG. **11**B, the method proceeds to process **1004** in which the near-field charging pad performs a coarse search (**1004**). In performing the coarse search **1004**, the near-field charging pad begins by enabling (**1122**) power for an antenna zone (e.g., antenna zone **290-1**, FIG. **1**B). In some embodiments, enabling power for the antenna zone includes transmitting, by an antenna element included in the antenna zone (e.g., after the RF power transmitter integrated circuit **160** provides one or more control signals to the switch **295** to activate the antenna zone), test power transmission signals with a first set of transmission characteristics (e.g., phase, gain, direction, amplitude, polarization, and/or frequency). Transmitting test power transmission signals is discussed in further detail above with reference to steps **916-918** of the method **900**.

Continuing with the coarse search **1004**, the near-field charging pad records (**1124**) an amount of power received by the wireless power receiver (the "reported power"). In some embodiments, the reported power is communicated to the near-field charging pad by the wireless power receiver via the communication channel that was established at operation **1110**.

The near-field charging pad repeats (**1126**) steps (**1122**) and (**1124**) above for all antenna zones that have been defined for the near-field charging pad (e.g., RF power transmitter integrated circuit **160** provides one or more control signals to the switch **295** to selectively activate all the antenna zones). Thereafter, in some embodiments, the near-field charging pad selects (**1128**) a set of antenna zones based on the reported power (e.g., **2** or **3** zones, or some greater or lesser number, depending on the circumstances) and a configured threshold (e.g., power-delivery criteria). For ease of discussion, each antenna zone in the set includes a single antenna **210** (e.g., antenna zone **290-1**, FIG. **1**B). However, it should be understood that instead of selecting a set of antenna zones, the near-field charging pad could also select a single antenna zone that includes multiple antennas **210**. For example, as shown in FIG. **1**B, the antenna zone **290**-N includes multiple antennas **210**. In addition, each antenna zone in the set could also include multiple antennas, depending on the circumstances.

Turning now to FIG. **11**C, after selecting the set of antenna zones based on the reported power, the near-field charging pad performs the fine search process (**1006**). In some embodiments, the fine search **1006** is used to determine which antenna zone(s) is/are best suited to wirelessly delivery power to the wireless power receiver, based on a location of the wireless power receiver on the near-field charging pad. In performing the fine search (**1006**), the near-field charging pad selects (**1132**) at least one antenna zone from the set of antenna zones selected using the coarse search, and for the at least one antenna zone, the near-field charging pad sweeps (**1134**) across available frequencies and/or impedances (i.e., tunes transmission of power transmission signals by the at least one antenna zone). Thereafter, the near-field charging pad records (**1136**) those characteristics that result in maximizing an amount of received power reported by the wireless power receiver. In some embodiments, operations **1134** and **1136** are repeated for each antenna zone in the set of antenna zones (**1138**) and the near-field charging pad selects (**1140**) an antenna zone (Z1) that delivers a maximum amount of power to the wireless power receiver. In addition, the near-field charging pad also records the frequency (and other transmission characteristics) and a relay position by antenna zone Z1 to achieve the delivery of the maximum amount of power to the wireless power receiver.

In some circumstances or situations, the amount of power delivered to the wireless power receiver by the antenna zone Z1 does not meet a threshold amount of power. In these circumstances or situations, the near-field charging pad performs an adjacent zone search (**1007**), which is illustrated in FIG. **11**D. In some embodiments, the adjacent zone search **1007** is used to identify one or more adjacent zones to the selected antenna zone Z1 that may be activated (e.g., the RF power transmitter integrated circuit **160** provides one or more control signals to the switch **295**) in order to increase an amount of power delivered to the wireless power receiver. For example, this may occur when the wireless power receiver is located at a border between adjacent antenna zones of the near-field charging pad (e.g., located at an intersection between two antenna zones, three antenna zones, or four antenna zones). In performing the adjacent zone search **1007**, the near-field charging pad identifies (**1142**) adjacent antenna zones (ZAs) to the selected antenna zone Z1. In some embodiments, identifying adjacent zones (ZAs) includes identifying up to five adjacent zones.

Next, the near-field charging pad pairs (**1144**) the selected antenna zone Z1 with each identified adjacent zone and sweeps (**1146**) across all antenna tuning combinations and sweeps (**1148**) across all available frequencies (and perhaps other transmission characteristics). Thereafter, the near-field charging pad selects (**1150**) a combination of antenna zones from among the adjacent zones (ZAs). For example, the near-field charging pad may determine that the selected antenna zone Z1 deliver a higher amount of power to the wireless power receiver than either of these antenna zones is individually able to deliver to the wireless power receiver. In another example, the near-field charging pad may determine that the selected antenna zone Z1 and two (or three) other adjacent zones deliver a maximum amount of power to the wireless power receiver. When selecting the desired combination of antenna zones, the near-field charging pad records the transmission characteristics used to produce the maximum amount of power delivered to the wireless power receiver. Performing the fine search and the adjacent zone search are also discussed in more detail above with reference to steps **924-932** of the method **900**.

After performing the fine search **1006** (and the adjacent zone search **1007** if needed), the near-field charging pad executes (**1008**) a power control routine, an example of which is illustrated in FIG. **11**E. In some embodiments, the power control routine allows both the wireless power receiver and the near-field charging pad to continually monitor an amount of power being delivered to the wireless power receiver. In this way, adjustments to the wireless power transmission can be made based on feedback received from the wireless power receiver. For example, if the delivered power is below a configured threshold, then the wireless power receiver may request a power increase from the near-field charging pad. FIG. **11**E illustrates various operations that may be used to allow the receiver to request an increase or a decrease in an amount of wireless power delivered to the receiver, and also illustrates a process executed by the near-field charging pad to determine when to increase or decrease the amount of wireless power delivered to the receiver in response to the receiver's requests for increases or decreases in the amount of wireless power delivered.

The antenna elements **120** described above (e.g., in reference to FIG. **1**B) may also be configured to have multiple adaptive load terminals (e.g., multiple adaptive load terminals **121**) that are coupled to at different positions along a respective antenna element **120**. An example of an antenna element **120** with multiple adaptive load terminals is provided below in reference to FIG. **12**. FIG. **12** is a schematic showing a transmitting antenna element (unit cell) with a plurality of adaptive loads (which may be a part of an array of such antennas, as described above in reference to FIGS. **3-8**) of an RF charging pad, in accordance with some embodiments. In some embodiments, the RF charging pad **1200** includes one or more antenna elements **1201** (which may be any of the antenna elements as shown in FIGS. **3**B, **4**, **6**A-**6**E, **7**A-**7**D, and **8**). Each antenna element **1201** is powered/fed by a respective power amplifier (PA) switch circuit **1208** (which may be a respective one of the PA switch circuits **103** of FIG. **3**A) that may be connected to a respective power amplifier **1208** or a source of power at a first end of the antenna element **1201**.

In some embodiments, the input circuit that includes the power amplifier **1208** may additionally include a device that can change frequencies of the input signal or a device that can operate at multiple frequencies at the same time, such as an oscillator or a frequency modulator.

In some embodiments, each antenna element **1201** of the RF charging pad **1200** includes a plurality of respective adaptive load terminals **1202**, for example, **1202***a*, **1202***b*, **1202***c*, . . . **1202***n*, at a plurality of positions within a respective antenna element **1201**. In some embodiments, the antenna element **1201** includes a conductive line forming a meandered line pattern (as discussed above in reference to FIGS. **3**, **4**, and **6-8**). In some embodiments, each adaptive load terminals of the plurality of adaptive load terminals **1202** for the antenna element **1201** is located at different positions on the conductive meandered line of the antenna element **1201** as shown in FIG. **12**.

In some embodiments, a meandered line antenna element **1201** includes a conductive line with multiple turns in one plane. In some embodiments, the multiple turns may be square turns as shown for the antenna element **1201** in FIG. **12**. In some embodiments, the multiple turns may be round-edged turns. The conductive line may also have segments of varying widths, for example, a segment **1206** having a first width, and short-length segment **1207** that has a second width that is less than the first width. In some embodiments, at least one of the adaptive load terminals **1202***a* is positioned at one of the short-length segments (e.g., short-length segment **1207**) and another adaptive load terminal is positioned anywhere at one of the segments **1206** having the first width. In some embodiments, at least one of the adaptive load terminals **1202** is positioned or connected anywhere on a width segment, for example, at the middle of a width segment of the meandered line antenna element **1201**. In some embodiments, the last adaptive load terminal **1202***n* is positioned at a second end of the conductive line (opposite to a first end at the input terminal **1203** of the antenna element **1201** described above in reference to FIGS. **3**, **4**, and **6-8**). In some embodiments, in certain design and optimization, an adaptive load terminal is not necessarily positioned at a second end of the meandered line antenna element **1201** but can be positioned at any location of the antenna element **1201**.

In some embodiments, the RF charging pad **1200** also includes (or is in communication with) a central processing unit **1210** (also referred to here as processor **1210**). In some embodiments, the processor **1210** is configured to control RF signal frequencies and to control impedance values at each of the adaptive load terminals **1202**, e.g., by communicating with a plurality of the load picks or adaptive loads **1212**, for example, **1212***a*, **1212***b*, **1212***c*, . . . **1212***n*, for each of the adaptive load terminals **1202** (as discussed above in reference to load pick or adaptive load **106** in FIGS. **3**A and **3**B).

In some embodiments, an electronic device (e.g., a device that includes a receiver **1204** as an internally or externally connected component, such as a remote that is placed on top of a charging pad **1200** that may be integrated within a housing of a streaming media device or a projector) and uses energy transferred from one or more RF antenna elements **1201** of the charging pad **1200** to the receiver **1204** to charge a battery and/or to directly power the electronic device.

In some embodiments, the adaptive load terminals **1202** at a particular zone or selected positions of the antenna element **1201** (e.g., a zone on the antenna element **1201** located underneath a position at which an electronic device (with an internally or externally connected RF receiver **1204**) to be charged is placed on the charging pad) are optimized in order to maximize power received by the receiver **1204**. For example, the CPU **1210** upon receiving an indication that an electronic device with an internally or externally connected RF receiver **1204** has been placed on the pad **1200** in a particular zone on the antenna element **1201** may adapt the plurality of adaptive loads **1212**, for example, adaptive loads **1212***a*, **1212***b*, **1212***c*, . . . **1212***n*, that are respectively coupled to the adaptive terminals **1202**, in order to maximize power transferred to the RF receiver **1204**. Adapting the set of adaptive loads **1212** may include the CPU **1210** commanding one or more of the adaptive loads to try various impedance values for one or more of the adaptive load terminals **1202** that are coupled to different positions of the antenna element **1201**. Additional details regarding adapting adaptive loads were provided above, and, for the sake of brevity, are not repeated here.

The effective impedance value ($Z_{effective}$) at a particular position/portion of the conductive line of the antenna element **1201** is affected by a number of variables and may be manipulated by adjusting configurations of the adaptive load terminals **1212** that are coupled to various positions on the antenna element **1201**. In some embodiments, an effective impedance value ($Z_{effective}$), starting from a point that divides sections **1225** (which starts at the terminal **1203** of the antenna element **1201** and extends to an edge of the receiver **1204**) and **1227** (which is formed by the rest of the transmitting antenna element **1201** and the terminal **1202***n*) and ending at the TX antenna **1201**'s connection to the adaptive load **1212***n* (e.g., terminal **1202***n*) will change based on location of the receiver **1204** on the TX antenna **1201** and based on a set of selected loads provided by adaptive loads **1212** at various positions within section **1227**. In some embodiments, the selected loads are optimized by the adaptive loads **1212** (in conjunction with the processor **1210**) to tune $Z_{effective}$ in such a way that the energy transferred between terminal **1203** and the receiver **1204** reaches a maximum (e.g., 75% or more of energy transmitted by antenna elements of the pad **1200** is received by the RF receiver **1204**, such as 98%), while energy transfer may also stay at a minimum from terminal **1203** to terminal **1202***n* (e.g., less than 25% of energy transmitted by antenna elements of the pad **1200** is not received by the RF receiver **1204** and ends up reaching terminals positioned within section **1227** or ends up being reflected back, including as little as 2%).

In some embodiments, a selected several adaptive loads **1212** of the plurality of adaptive loads **1212** are used (by the processor **1210**) on the antenna element **1201** to adjust the impedance and/or frequency of the antenna element **1201**. In one example, with reference to FIG. **12**, only adaptive load terminals **1202***a* and **1202***c* are connected at a particular point in time to adaptive loads **1212***a* and **1212***c* respectively, while adaptive load terminals **1202***b* and **1202***n* are disconnected at the particular point in time. In another example, with reference to FIG. **12**, only adaptive load terminals **1202***a* and **1202***n* are connected at a particular point in time to adaptive loads **1212***a* and **1212***n*, respectively, while adaptive load terminals **1202***b* and **1202***c* are disconnected at the particular point in time. In some embodiments, all of the adaptive load terminals **1202** are connected at a particular point in time to their respective adaptive loads **1212**. In some embodiments, none of the adaptive load terminals **1202** are connected at a particular point in time to their respective adaptive loads **1212**. In some embodiments, the impedance value of each of the adaptive loads **1212** connected to a selected adaptive load terminal **1212** is adjusted individually to optimize the energy transfer.

In embodiments in which a meandered line antenna has been optimized for the multi-band operation, the multiple adaptive load configuration within a single antenna element also enables a broader frequency band adjustment compared with a single adaptive load configuration within a single antenna element as described in FIG. **3**B above. The multiple adaptive load configuration within a single antenna element further enhances multiple frequency band operation on a single antenna element. For example, a single antenna element **1201** with multiple adaptive load terminals is capable of operating at a wider frequency band than a corresponding antenna element that is configured with one adaptive load terminal.

In some embodiments, adapting the set of adaptive loads **1212** also or alternatively includes the CPU **1210** causing the set of antenna elements to transmit RF signals at various frequencies until a frequency is found at which a maximum amount of energy is transferred to the RF receiver **1204**. In some embodiments, for example, one of the antenna elements transmits RF signals at a first frequency, and another one of the antenna elements transmits RF signals at a second frequency that is different from the first frequency. In some embodiments, adjusting the impedance value and/or the frequencies at which the set of antenna elements transmits causes changes to the amount of energy transferred to the RF receiver **1204**. In this way, the amount of energy transferred to the RF receiver **1204** that is maximized (e.g., to transfer at least 75% of the energy transmitted by antenna elements of the pad **1200** to the receiver **1204**, and in some embodiments, adjusting the impedance value and/frequencies may allow up to 98% of the energy transmitted to be received by the receiver **1204**) may be received at any particular point on the pad **1200** at which the RF receiver **1204** might be placed.

In some embodiments, the CPU **1210** determines that a maximum amount of energy is being transferred to the RF receiver **1204** when the amount of energy transferred to the RF receiver **1204** crosses a predetermined threshold (e.g., 75% or more of transmitted energy is received, such as up to 98%) or by testing transmissions with a number of impedance and/or frequency values and then selecting the combination of impedance and frequency that results in maximum energy being transferred to the RF receiver **1204** (also as described in reference to the adaptation scheme in FIGS. **3**A-**3**D above). In some embodiments, processor **1210** is connected to the receiver **1204** through a feedback loop (e.g. by exchanging messages using a wireless communication protocol, such as BLUETOOTH low energy (BLE), WIFI, ZIGBEE, infrared beam, near-field transmission, etc, to exchange messages). In some embodiments, the adaptation scheme is employed to test various combinations of impedance values of the adaptive impedance loads **1212** and RF frequencies, in order to maximize energy transferred to an RF receiver **1204**. In such embodiments, each of the adaptive load **1212** is configured to adjust the impedance value along a range of values, such as between 0 and infinity. In some embodiments, the adaptation scheme is employed when one or more RF receivers are placed on top of one of the antenna element **1201**.

In some embodiments, an adaptation scheme is employed to adaptively adjust the impedance values and/or frequencies of the RF signal(s) emitted from the RF antenna(s) **1201** of the charging pad **1200**, in order to determine which combinations of frequency and impedance result in maximum energy transfer to the RF receiver **1204**. For example, the processor **1210** that is connected to the charging pad **1200** tries different frequencies (i.e., in the allowed operating frequency range or ranges) by using different selected sets of adaptive loads **1212** at different locations of the antenna element **1201**, e.g. enabling or disabling certain adaptive loads **1212**, to attempt to adaptively optimize for better performance. For example, a simple optimization either opens/disconnects or closes/shorts each load terminal to ground (in embodiments in which a relay is used to switch between these states), and may also cause RF antenna element **1201** to transmit at various frequencies. In some embodiments, for each combination of relay state (open or shorted) and frequency, the energy transferred to the receiver **1204** is monitored and compared to energy transferred when using other combinations. The combination that results in maximum energy transfer to the receiver **1204** is selected and used to continue to transmitting the one or more RF signals using one or more antenna elements **1201** to the receiver **1204**.

In some embodiments, the single antenna element **1201** with multiple adaptive loads **1212** of the pad **1200** may be configured to operate in two or more distinct frequency bands (such as the ISM bands described above), e.g., a first frequency band with a center frequency of 915 MHz and a second frequency band with a center frequency of 5.8 GHz. In these embodiments, employing the adaptation scheme may include transmitting RF signals and then adjusting the frequency at first predetermined increments until a first threshold value is reached for the first frequency band and then adjusting the frequency at second predetermined increments (which may or may not be the same as the first predetermined increments) until a second threshold value is reached for the second frequency band. In some embodiments, a single antenna element can operate at multiple different frequencies within one or more frequency bands. For example, the single antenna element **1201** may be configured to transmit at 902 MHz, 915 MHz, 928 MHZ (in the first frequency band) and then at 5.795 GHz, 5.8 GHz, and 5.805 GHz (in the second frequency band). The single antenna element **1201** can operate at more than one frequency bands as a multi-band antenna. A transmitter with at least one antenna element **1201** can be used as a multi-band transmitter.

In some embodiments, multiple antenna elements **1201** each with multiple adaptive loads **1212** may be configured within a particular transmission pad to allow the particular transmission pad to operate in two or more distinct frequency bands respectively at the same time. For example, a first antenna element **1201** of the particular transmission pad operates at a first frequency or frequency band, a second antenna element **1201** of the particular transmission pad operates at a second frequency or frequency band, and a third antenna element **1201** of the particular transmission pad operates at a third frequency or frequency band, and a fourth antenna element **1201** of the particular transmission pad operates at a fourth frequency or frequency band, and the four frequency bands are distinct from each other. In this way, the particular transmission pad is configured to operate at multiple different frequency bands.

In some embodiments, the transmitter described herein can transmit wireless power in one frequency or frequency band, and transmit and exchange data with a receiver in another frequency or frequency band.

Different antenna elements operating at different frequencies can maximize energy transfer efficiency when a smaller device is charged with higher frequencies and a larger device is charged with lower frequencies on the same charging pad. For example, devices that require a higher amount of power, such as mobile phones, may also have more space to include larger antennas, thus making a lower frequency of 900 MHz a suitable frequency band. As a comparison, a smaller device, such as an earbud, may require a small amount of power and may also have less space available for longer antennas, thus making a higher frequency of 2.4 or 5.8 GHz a suitable frequency band. This configuration enables more flexibility in the types and sizes of antennas that are included in receiving devices.

Turning now to FIG. **13**, in accordance with some embodiments, a flow chart of a method **1300** of charging an electronic device through radio frequency (RF) power transmission by using at least one RF antenna with a plurality of adaptive loads is provided. Initially, a charging pad including a transmitter is provided in step **1302** that includes at least one RF antenna (e.g., antenna element **1201**, as described with respect to FIG. **12** above which further includes FIGS. **3**-**8**) for transmitting one or more RF signals or waves, i.e., an antenna designed to and capable of transmitting RF electromagnetic waves. In some embodiments, an array of RF antenna elements **1201** are arranged adjacent to one another in a single plane, in a stack, or in a combination of thereof, thus forming an RF charging pad **1200** (as described in reference to FIGS. **6**A-**6**E, **7**A-**7**D and **8**). In some embodiments, the RF antenna elements **1201** each include an antenna input terminal (e.g., the first terminal **1203** discussed above in reference to FIG. **12**) and a plurality of antenna output terminals (e.g., the plurality of adaptive load terminals **1202** discussed above in reference to FIG. **12**). In some embodiments, the antenna element **1201** includes a conductive line that forms a meandered line arrangement (as shown in FIGS. **3**-**4**, and **6**-**12**). The plurality of adaptive load terminals **1202** are positioned at different locations of the conductive line of the antenna element **1201**.

In some embodiments, the transmitter further comprises a power amplifier electrically coupled between the power input and the antenna input terminal (e.g., PA **1208** in FIG. **12**). Some embodiments also include respective adaptive loads **1212***a*, **1212***b*, **1212***c*, . . . **1212***n* electrically coupled to the plurality of antenna output terminals (e.g., adaptive load terminals **1202** in FIG. **12**). In some embodiments, the transmitter includes a power input configured to be electrically coupled to a power source, and at least one processor (e.g., processor **1210** in FIG. **12**, and processor **110** in FIGS. **3**A-**3**B) configured to control at least one electrical signal sent to the antenna. In some embodiments, the at least one processor is also configured to control the frequency and/or amplitude of the at least one signal sent to the antenna.

In some embodiments, each RF antenna of the transmitter includes: a conductive line forming a meandered line pattern, a first terminal (e.g., terminal **1203**) at a first end of the conductive line for receiving current that flows through the conductive line at a frequency controlled by one or more processors, and a plurality of adaptive load terminals (e.g., terminals **1202**), distinct from the first terminal, at a plurality of positions of the conductive line, the plurality of adaptive load terminals coupled to a respective component (e.g., adaptive loads **1212** in FIG. **12**) controlled by the one or more processors and that allows for modifying an impedance value of the conductive line. In some embodiments, the conductive line is disposed on or within a first antenna layer of a multi-layered substrate. Also in some embodiments, a second antenna is disposed on or within a second antenna layer of the multi-layered substrate. Finally, some embodiments also provide a ground plane disposed on or within a ground plane layer of the multi-layered substrate.

In some embodiments, a receiver (e.g., receiver **1204** in reference to FIG. **12**) is also provided (also as described in reference to FIG. **3**). The receiver also includes one or more RF antennas for receiving RF signals. In some embodiments, the receiver includes at least one rectenna that converts the one or more RF signals into usable power to charge a device that includes the receiver **1204** as an internally or externally connected component (see also steps **504**, **506**, **510**, **514** and **518** in reference to FIG. **5**). In use, the receiver **1204** is placed within a near-field radio frequency distance to the at least one antenna of the transmitter or the charging pad. For example, the receiver may be placed on top of the at least one RF antenna **1201** or on top of a surface that is adjacent to the at least one RF antenna **1201**, such as a surface of a charging pad **1200**.

In step **1304**, one or more RF signals are then transmitted via at the least one RF antenna **1201**.

The system is then monitored in step **1306** to determine the amount of energy that is transferred via the one or more RF signals from the at least one antenna **1201** to one or more RF receivers (as is also discussed above). In some embodiments, this monitoring **1306** occurs at the transmitter, while in other embodiments the monitoring **1306** occurs at the receiver which sends data back to the transmitter via a back channel (e.g., over a wireless data connection using WIFI or BLUETOOTH). In some embodiments, the transmitter and the receiver exchange messages via the back channel, and these messages may indicate energy transmitted and/or received, in order to inform the adjustments made at step **1308**.

In some embodiments, in step **1308**, a characteristic of the transmitter is adaptively adjusted to attempt to optimize the amount of energy that is transferred from the at least one RF antenna **1201** to the receiver. In some embodiments, this characteristic is a frequency of the one or more RF signals and/or an impedance of the transmitter. In some embodiments, the impedance of the transmitter is the impedance of the adjustable loads. Also in some embodiments, the at least one processor is also configured to control the impedance of the selected set of the plurality of adaptive loads **1212**. Additional details and examples regarding impedance and frequency adjustments are provided above.

In some embodiments, the at least one processor (e.g. CPU **1210** in FIG. **12**) dynamically adjusts the impedance of the adaptive load based on the monitored amount of energy that is transferred from the at least one antenna **1201** to the RF receiver. In some embodiments, the at least one processor simultaneously controls the frequency of the at least one signal sent to the antenna.

In some embodiments, the single antenna element **1201** with multiple adaptive loads **1212** of the pad **1200** may be dynamically adjusted by the one or more processors to operate in two or more distinct frequency bands (such as the ISM bands described above) at the same time or at different times, e.g., a first frequency band with a center frequency of 915 MHz and a second frequency band with a center frequency of 5.8 GHz. In these embodiments, employing the adaptation scheme may include transmitting RF signals and then adjusting the frequency at first predetermined increments until a first threshold value is reached for the first frequency band and then adjusting the frequency at second predetermined increments (which may or may not be the same as the first predetermined increments) until a second threshold value is reached for the second frequency band. For example, the single antenna element **1201** may be configured to transmit at 902 MHz, 915 MHz, 928 MHZ (in the first frequency band) and then at 5.795 GHz, 5.8 GHz, and 5.805 GHz (in the second frequency band). The single antenna element **1201** can operate at more than one frequency bands as a multi-band antenna. A transmitter with at least one antenna element **1201** can be used as a multi-band transmitter.

In some embodiments, a charging pad or transmitter may include one or more of the antenna element **1201** with a plurality of adaptive loads as described in FIG. **12** and one or more antenna element **120** with one adaptive load as described in FIG. **3**A-**3**D.

FIGS. **14**A-**14**D are schematics showing various configurations for individual antenna elements that can operate at multiple frequencies or frequency bands within an RF charging pad, in accordance with some embodiments. As shown in FIGS. **14**A-**14**D, an RF charging pad **100** (FIGS. **3**A-**3**B) or an RF charging pad **1200** (FIG. **12**) may include antenna elements **120** (FIG. **3**B) or **1201** (FIG. **12**) that configured to have conductive line elements that have varying physical dimensions.

For example, FIGS. **14**A-**14**D show examples of structures for an antenna element that each include a conductive line formed into different meandered line patterns at different portions of the element. The conductive lines at different portions or positions of the element may have different geometric dimensions (such as widths, or lengths, or trace gauges, or patterns, spaces between each trace, etc.) relative to other conductive lines within an antenna element. In some embodiments, the meandered line patterns may be designed with variable lengths and/or widths at different locations of the pad (or an individual antenna element). These configurations of meandered line patterns allow for more degrees of freedom and, therefore, more complex antenna structures may be built that allow for wider operating bandwidths and/or coupling ranges of individual antenna elements and the RF charging pad.

In some embodiments, the antennas elements **120** and **1201** described herein may have any of the shapes illustrated in FIGS. **14**A-**14**D. In some embodiments, each of the antenna elements shown in FIGS. **14**A-**14**D has an input terminal (**123** in FIG. **1**B or **1203** in FIG. **12**) at one end of the conductive line and at least one adaptive load terminals (**121** in FIG. **1**B or **1202***a-n* in FIG. **12**) with adaptive loads (**106** in FIG. **1**B or **1212***a-n* in FIG. **12**) as described above at another end or a plurality of positions of the conductive line.

In some embodiments, each of the antenna elements shown in FIGS. **14**A-**14**D can operate at two or more different frequencies or two or more different frequency bands. For example, a single antenna element can operate at a first frequency band with a center frequency of 915 MHz at a first point in time and a second frequency band with a center frequency of 5.8 GHz at a second point in time, depending on which frequency is provided at an input terminal of each of the antenna elements. Moreover, the shapes of the meandered line patterns shown in FIGS. **14**A-**14**D are optimized to allow the antenna elements to operate efficiently at multiple different frequencies.

In some embodiments, each of the antenna elements shown in FIGS. **14**A-**14**D can operate at two or more different frequencies or two or more different frequency bands at the same time when the input terminal is supplied with more than two distinct frequencies that can be superimposed. For example, a single antenna element can operate at a first frequency band with a center frequency of 915 MHz and a second frequency band with a center frequency of 5.8 GHz at the same time when both frequency bands with a first center frequency of 915 MHz and a second center frequency of 5.8 GHz are supplied at the input terminal of the conductive line. In yet another example, a single antenna element can operate at multiple different frequencies within one or more frequency bands.

In some embodiments, the operating frequencies of the antenna elements can be adaptively adjusted by one or more processors (**110** in FIGS. **3**A-**3**B or **1210** in FIG. **12**) as described above according to the receiver antenna dimension, frequency, or the receiver loads and the adaptive loads on the charging pad.

In some embodiments, each of the antenna elements shown in FIGS. **14**A-**14**D with different meandered patterns at different portions of the conductive line can operate more efficiently at multiple frequencies compared with the more symmetrical meandered line structures (For example, FIG. **3**B, **4**, **6**A-**6**B, or **8**). For example, energy transfer efficiency at different operating frequencies of the antenna elements shown in FIGS. **14**A-**14**D with different meandered patterns at different portions of the conductive line can be improved by about at least 5%, and in some instance at least 60%, more than the more symmetrical meandered line structure elements. For example, the more symmetrical meandered line structure antenna element may be able to transfer no more than 60% of transmitted energy to a receiving device while operating at a new frequency other than a frequency for which the more symmetrical meandered line structure antenna element has been designed (e.g., if the more symmetrical meandered line structure antenna element is designed to operate at 900 MHz, if it then transmits a signal having a frequency of 5.8 GHz it may only be able to achieve an energy transfer efficiency of 60%). In contrast, the antenna element with different meandered patterns (e.g., those shown in FIGS. **14**A-**14**D) may be able to achieve an energy transfer efficiency of 80% or more while operating at various frequencies. In this way, the designs for antenna elements shown in FIGS. **14**A-**14**D ensure that a single antenna element is able to achieve a more efficient operation at various different frequencies.

FIG. **15** is schematic showing an example configuration for an individual antenna element that can operate at multiple frequencies or frequency bands by adjusting the length of the antenna element, in accordance with some embodiments.

In some embodiments as shown in FIG. **15**, at least one transmitting antenna element **1502** (as described in FIGS. **3**-**8** and **13**-**14**) of the one or more transmitting antenna elements of an RF charging pad **1500** has a first conductive segment **1504** (a first portion of a meandered conductive line, such as any of those described above for antenna elements **120** and **1201**) and a second conductive segment **1506** (a second portion of the meandered conductive line, such as any of those described above for antenna elements

120 and **1201**). In some embodiments, the first conductive segment includes an input terminal (**123** in FIG. **3**B or **1203** in FIG. **12**). In some embodiments, the at least one transmitting antenna element **1502** is configured to operate at a first frequency (e.g., 2.4 GHz) while the first conductive segment **1504** is not coupled with the second conductive segment **1506**. In some embodiments, the at least one transmitting antenna element **1502** is configured to operate at a second frequency (e.g., 900 MHz) which is different from the first frequency while the first conductive segment is coupled with the second conductive segment.

In some embodiments, one or more processors (**110** in FIGS. **3**A-**3**B or **1210** in FIG. **12**) are configured to cause coupling of the first segment with the second segment in conjunction with instructing a feeding element (as described as **108** in FIGS. **3**A-**3**B and **1208** in FIG. **12**) to generate current with a second frequency (e.g., 900 MHz) that is distinct from the first frequency (e.g., 2.4 GHz), thereby allowing the antenna element **1502** to more efficiently operate at the second frequency. The one or more processor may also be configured to cause de-coupling of the second conductive segment from the first conductive segment in conjunction with instructing the feeding element to generate current with the first frequency instead of the second frequency, thereby allowing the antenna element **1502** to more efficiently operate at the first frequency again. In some embodiments, the one or more processors are configured to determine whether to causing the coupling (or de-coupling) of these conductive segments based on information received from a receiver (e.g., RX **104** or **1204**) that identifies a frequency at which the receiver is configured to operate (e.g., for larger devices with longer receiving antennas, this frequency may be 900 MHz, while for smaller devices with small receiving antennas, this frequency may be 2.4 GHz).

In some embodiments, the coupling described here in FIG. **15** can be implemented by directly connecting two different segments of a single antenna element **1502** while bypassing the conductive line located in-between the two connection points or the two different segments. In some embodiments, coupling can be implemented between more than two different segments of the antenna element **1502**. The coupling of the different portions or segments of a single meandered line antenna element **1502** can effectively change the size or length of the conductive line of the antenna element **1502**, and therefore enable the single antenna element **1502** to operate at different frequencies. The single antenna element **1502** may also operate at more than one frequency bands as a multi-band antenna.

FIG. **16**A shows a top perspective view of a schematic drawing of an exemplary near-field power transfer system **1600**. FIG. **16**B shows a bottom perspective view of a schematic drawing of an exemplary near-field power transfer system **1600**. The power transfer system **1600** may comprise a top surface **1601**, a bottom surface **1602**, and sidewalls **1603**. In some embodiments, a housing containing components of the power transfer system **1600** may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **1601** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **1603** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

The power transfer system **1600** may radiate RF energy and thus transfer power when the power transfer system **1600** is adjacent to a second power transfer system (not shown). As such, a power transfer system **1600** may be on a "transmit side," so as to function as a power transmitter, or the power transfer system **1600** may be on a "receive side," so as to function as a power receiver. In some embodiments, where the power transfer system **1600** is associated with a transmitter, the power transfer system **1600** (or subcomponents of the power transfer system **1600**) may be integrated into the transmitter device, or may be externally wired to the transmitter. Likewise, in some embodiments, where the power transfer system **1600** is associated with a receiver, the power transfer system **1600** (or subcomponents of the power transfer system **1600**) may be integrated into the receiver device, or may be externally wired to the receiver.

A substrate **1607** may be disposed within a space defined between the top surface **1601**, sidewalls **1603**, and the bottom surface **1602**. In some embodiments, the power transfer system **1600** may not include a housing and the substrate **1607** may include the top surface **1601**, sidewalls **1603**, and the bottom surface **1602**. The substrate **1607** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may generate radiation, and may act as thin reflectors.

An antenna **1604** may be constructed on or below the top surface **1601**. When the power transfer system **1600** is associated with a power transmitter, the antenna **1604** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **1600** is associated with a power receiver, the antenna **1604** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **1600** may operate as a transceiver and the antenna **1604** may both transmit and receive electromagnetic waves. The antenna **1604** may be constructed from materials such as metals, alloys, metamaterials and composites. For example, the antenna **1604** may be made of copper or copper alloys. The antenna **1604** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **1600** shown in FIG. **16**A and FIG. **16**B, the antenna **1604** is constructed in a shape of a spiral including antenna segments **1610** that are disposed close to each other. The currents flowing through the antenna segments **1610** may be in opposite directions. For example, if the current in the antenna segment **1610***b* is flowing from left to right of FIG. **16**A, the current each of the antenna segments **1610***a*, **1610***c* may be flowing from right to left. The opposite flow of the current results in mutual cancellation of the electromagnetic radiation the far field of the power transfer system **1600**. In other words, the far field electromagnetic radiation generated by one or more antenna segments **1610** left of an imaginary line **1615** is cancelled out by the far field electromagnetic radiation generated by one or more antenna segments **1610** right of the line **1615**. Therefore, there may be no leakage of power in the far field of the power transfer system **1600**. Such cancellation, however, may not occur in a near-field active zone of the power transfer system **1600**, where the transfer of power may occur.

The power transfer system **1600** may include a ground plane **1606** at or above the bottom surface **1602**. The ground plane **1606** may be formed by materials such as metal, alloys, and composites. In an embodiment, the ground plane **1606** may be formed by copper or a copper alloy. In some embodiments, the ground plane **1606** may be constructed of a solid sheet of material. In other embodiments, the ground plane **1606** may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. A via **1605** carrying a power feed line (not shown) to the antenna may pass through the ground plane **1606**. The power feed line may supply current to the antenna **1604**. In some embodiments, the ground plane **1606** may be electrically connected to the antenna **1604**. In some embodiments, the ground plane **1606** may not be electrically connected to the antenna **1604**. For such implementations, an insulation area **1608** to insulate the via **1605** from the ground plane **1606** may be constructed between the via **1605** and the ground plane **1606**. In some embodiments, the ground plane **1606** may act as a reflector of the electromagnetic waves generated by the antenna **1604**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **1600** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antenna **1604** from or towards the top surface **1601**. Therefore, there may be no leakage of electromagnetic power from the bottom surface **1602**.

Therefore, as a result of the antenna **1604** and the ground plane **1606**, the electromagnetic waves transmitted or received by the power transfer system **1600** accumulate in the near field of the system **1600**. The leakage to the far field of the system **1600** is minimized.

FIG. **17**A schematically illustrates a top perspective view of an exemplary near-field power transfer system **1700**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **1700** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **1700** may be a part of or associated with a power receiver. The power transfer system **1700** may comprise a housing defined by a top surface **1701**, a bottom surface (not shown), and sidewalls **1703**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **1701** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **1703** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **1707** may be disposed within a space defined between the top surface **1701**, sidewalls **1703**, and the bottom surface **1702**. In some embodiments, the power transfer system **1700** may not include a housing and the substrate **1707** may include the top surface **1701**, sidewalls **1703**, and the bottom surface **1702**. The substrate **1707** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may generate radiation, and may act as thin reflectors.

An antenna **1704** may be constructed on or below the top surface **1701**. When the power transfer system **1700** is a part of or associated with a power transmitter, the antenna **1704** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **1700** is a part of or associated with a power receiver, the antenna **1704** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **1700** may operate as a transceiver and the antenna **1704** may both transmit and receive electromagnetic waves. The antenna **1704** may be constructed from materials such as metals, alloys, metamaterials, and composites. For example, the antenna **1704** may be made of copper or copper alloys. The antenna **1704** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **1700** shown in FIG. **17**A the antenna **1704** is constructed in a shape of a spiral including antenna segments which are disposed close to each other. A signal feed line (not shown) may be connected to the antenna **1704** through a via **1705**.

FIG. **17**B schematically illustrates a side view of the exemplary power transmission system **1700**. As shown, an upper metal layer may form the antenna **1704**, and a lower metal layer may form the ground plane **1706**. The substrate **1707** may be disposed in between the upper and lower metal layer. The substrate **1707** may include materials such as FR4, metamaterials, or any other materials known in the art. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may have to be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or generate radiation, and may act as thin reflectors.

FIG. **17**C schematically illustrates a top perspective view of antenna **1704**. The antenna **1704** comprises a connection point **1709** for a feed line (not shown) coming through the via **1705**. FIG. **17**D schematically illustrates a side perspective view of the ground plane **1706**. In an embodiment, the ground plane **1706** comprises a solid metal layer. In other embodiments, the ground plane **1706** may include structures such as stripes, meshes, and lattices and may not be completely solid. The ground plane **1706** may also comprise a socket **1709** for the via **1705** to pass through. Around the socket **1709**, the ground plane **1706** may also include an insulating region **1710** to insulate the socket **1709** from the rest of the ground plane **1706**. In some embodiments, the ground plane may have an electrical connection to a line coming through the via, and the insulating region **1710** may not be required.

FIG. **18** schematically illustrates a top perspective view of an exemplary near-field power transfer system **1800**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **1800** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **1800** may be a part of or associated with a power receiver. The power transfer system **1800** may comprise a housing defined by a top surface **1801**, a bottom surface (not shown), and sidewalls **1803**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **1801** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **1803** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **1807** may be disposed within a space defined between the top surface **1801**, sidewalls **1803**, and the bottom surface **1802**. In some embodiments, the power transfer system **1800** may not include a housing and the substrate **1807** may include the top surface **1801**, sidewalls **1803**, and the bottom surface **1802**. The substrate **1807** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may transmit radiation, and may act as thinreflectors.

An antenna **1804** may be constructed on or below the top surface. When the power transfer system **1800** is a part of or associated with a power transmitter, the antenna **1804** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **1800** is a part of or associated with a power receiver, the antenna **1804** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **1800** may operate as a transceiver and the antenna **1804** may both transmit and receive electromagnetic waves. The antenna **1804** may be constructed from materials such as metals, alloys, metamaterials and composites. For example, the antenna **1804** may be made of copper or copper alloys. The antenna **1804** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **1800** shown in FIG. **18**, the antenna **1804** is constructed in a shape of a dipole including a first meandered pole **1809***a* and a second meandered pole **1809***b*. A first power feed line (not shown) to the first meandered pole **1809***a* may be carried by a first via **1805***a* and a second power feed line (not shown) to the second meandered pole **1809***b* may be carried by a second via **1805***b*. The first power feed line may supply current to the first meandered pole **1809***a* and the second power feed line may supply current to the second meandered pole **1809***b*. The first meandered pole **1809***a* includes antenna segments **1810** which are disposed close to each other and the second meandered pole **1809***b* includes antenna segments **1811** also disposed close to each other. The currents flowing through the neighboring antenna segments **1810**, **1811** may be in opposite directions. For example, if the current in an antenna segment **1810***b* is flowing from left to right of FIG. **18**, the current in each of the antenna segments **1810***a*, **1810***c* may be flowing from right to left. The opposite flow of the current across any number of antenna segments **1810** of the power transfer system **1800** results in mutual cancellation of the far field electromagnetic radiation generated by the power transfer system **1800**. Additionally or alternatively, the far field electromagnetic radiation generated by the antenna segments **1810** of the first pole **1809***a* may be cancelled by the electromagnetic radiation generated by antenna segments **1811** of the second pole **1809***b*. It should be appreciated that the far field cancellation may occur across any number of segments **1810**, **1811** and/or across any number of poles **1809**. Therefore, there may be no leakage of power in the far field of the power transfer system **1800**. Such cancellation, however, may not occur in a near-field active zone of the power transfer system **1800**, where the transfer of power may occur.

The power transfer system **1800** may include a ground plane (not shown) at or above the bottom surface. The ground plane may be formed by materials such as metal, alloys, and composites. In an embodiment, the ground plane may be formed by copper or a copper alloy. In some embodiments, the ground plane may be constructed of a solid sheet of material. In other embodiments, the ground plane may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. The vias **1805** carrying the power feed lines to the antenna may pass through the ground plane. In some embodiments, the ground plane may be electrically connected to the antenna. In some embodiments, the ground plane may not be electrically connected to the antenna **1804**. For such implementations, an insulation area to insulate the vias **1805** from the ground plane may be constructed between the vias **1805** and the ground plane. In some embodiments, the ground plane may act as a reflector of the electromagnetic waves generated by the antenna **1804**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **1800** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antenna **1804** from or towards the top surface **1801**. Therefore, there may be no leakage of electromagnetic power from the bottom surface.

FIG. **19** schematically illustrates a top perspective view of an exemplary near-field power transfer system **1900**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **1900** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **1900** may be a part of or associated with a power receiver. The power transfer system **1900** may comprise a housing defined by a top surface **1901**, a bottom surface (not shown), and sidewalls **1903**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **1901** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **1903** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **1907** may be disposed within a space defined between the top surface **1901**, sidewalls **1903**, and the bottom surface **1902**. In some embodiments, the power transfer system **1900** may not include a housing and the substrate **1907** may include the top surface **1901**, sidewalls **1903**, and the bottom surface **1902**. The substrate **1907** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may generate radiation, and may act as thinreflectors.

An antenna **1904** may be constructed on or below the top surface **1901**. When the power transfer system **1900** is a part of or associated with a power transmitter, the antenna **1904** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **1900** is a part of or associated with a power receiver, the antenna **1904** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **1900** may operate as a transceiver and the antenna **1904** may both transmit and receive electromagnetic waves. The antenna **1904** may be constructed from materials such as metals, alloys, and composites. For example, the antenna **1904** may be made of copper or copper alloys. The antenna **1904** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **1900** shown in FIG. **19**, the antenna **1904** is constructed in a shape of a loop including loop segments **1910** which are disposed close to each other. The currents flowing through the neighboring loop segments **1910** may be in opposite directions. For example, if the current in a first loop segment **1910***a* is flowing from left to right of FIG. **19**, the current in a second loop segment **1910***b* may be flowing from right to left. The opposite flow of the current results in mutual cancellation of the electromagnetic radiation the far field of the power transfer system **1900**. Therefore, there may be no leakage of power in the far field of the power transfer system **1900**. Such cancellation, however, may not occur in a near-field active zone of the power transfer system **1900**, where the transfer of power may occur.

The power transfer system **1900** may include a ground plane (not shown) at or above the bottom surface. The ground plane may be formed by materials such as metal, alloys, metamaterials, and composites. In an embodiment, the ground plane may be formed by copper or a copper alloy. In some embodiments, the ground plane may be constructed of a solid sheet of material. In other embodiments, the ground plane may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. The vias **1905** carrying the power feed lines (not shown) to the antenna may pass through the ground plane. The power feed lines may provide current to the antenna **1904**. In some embodiments, the ground plane **106** may be electrically connected to the antenna. In some embodiments, the ground plane may not be electrically connected to the antenna **1904**. For such implementations, an insulation area to insulate the vias **1905** from the ground plane may be constructed between the vias **305** and the ground plane. In some embodiments, the ground plane may act as a reflector of the electromagnetic waves generated by the antenna **1904**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **300** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antenna **1904** from or towards the top surface **1901**. Therefore, there may be no leakage of electromagnetic power from the bottom surface.

FIG. **20** schematically illustrates a top perspective view of an exemplary near-field power transfer system **2000**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **2000** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **2000** may be a part of or associated with a power receiver. In other embodiments, the power transfer system **2000** may be a part of or associated with a transceiver. The power transfer system **2000** may comprise a housing defined by a top surface **2001**, a bottom surface (not shown), and sidewalls **2003**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **2001** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **2003** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **2007** may be disposed within a space defined between the top surface **2001**, sidewalls **2003**, and the bottom surface **2002**. In some embodiments, the power transfer system **2000** may not include a housing and the substrate **2007** may include the top surface **2001**, sidewalls **2003**, and the bottom surface **2002**. The substrate **2007** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting cmTent, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may transmit radiation, and may act as thinreflectors.

An antenna **2004** may be constructed on or below the top surface **2001**. When the power transfer system **2000** is a part of or associated with a power transmitter, the antenna **2004** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **2000** is a part of or associated with a power receiver, the antenna **2004** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **2000** may operate as a transceiver and the antenna **2004** may both transmit and receive electromagnetic waves. The power feed lines (not shown) to the antenna **2004** may be carried by the vias **2005**. The power feed lines may provide current to the antenna **2004**. The antenna **2004** may be constructed from materials such as metals, alloys, metamaterials, and composites. For example, the antenna **2004** may be made of copper or copper alloys. The antenna **2004** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **2000** shown in FIG. **20**, the antenna **2004** is constructed in a shape of concentric loops including antenna segments **2010** which are disposed close to each other. As shown in FIG. **20**, a single concentric loop may include two of the antenna segments **2010**. For example, the innermost loop may include a first antenna segment **2010***c* to the right of an imaginary line **2012** roughly dividing the loops into two halves, and a corresponding second antenna segment **2010***c*' to the left of the imaginary line **2012**. The currents flowing through the neighboring antenna segments **2010** may be in opposite directions. For example, if the current in the antenna segments **2010***a*', **2010***b*', **2010***c*' is flowing from left to right of FIG. **20**, the current in each of the antenna segments **2010***a*, **2010***b*, **2010***c* may be flowing from right to left. The opposite flow of the current results in mutual cancellation of the electromagnetic radiation at the far field of the power transfer system **2000**. Therefore, there may be no transfer of power to the far field of the power transfer system **2000**. Such cancellation, however, may not occur in a near-field active zone of the power transfer system **2000**, where the transfer of power may occur. One ordinarily skilled in the art will appreciate the cancellation of electromagnetic radiation in the far field and absence of such cancellation in the near-field is dictated by one or more solutions of Maxwell's equations for time-varying electric and magnetic fields generated by the currents flowing in opposite directions. One ordinarily skilled in the art should further appreciate the near field active zone is defined by the presence of electromagnetic power in the immediate vicinity of the power transfer system **2000**.

The power transfer system **2000** may include a ground plane (not shown) at or above the bottom surface. The ground plane may be formed by materials such as metal, alloys, and composites. In an embodiment, the ground plane may be formed by copper or a copper alloy. In some embodiments, the ground plane may be constructed of a solid sheet of material. In other embodiments, the ground plane may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. The vias **2005** carrying the power feed lines to the antenna may pass through the ground plane. In some embodiments, the ground plane may be electrically connected to the antenna. In some embodiments, the ground plane may not be electrically connected to the antenna **2004**. For such implementations, an insulation area to insulate the vias **2005** from the ground plane may be constructed between the vias **2005** and the ground plane. In some embodiments, the ground plane may act as a reflector of the electromagnetic waves generated by the antenna **2004**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **2000** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antenna **2004** from or towards the top surface **2001**. Therefore, there may be no leakage of electromagnetic power from the bottom surface.

FIG. **21** schematically illustrates a top perspective view of an exemplary near-field power transfer system **2100**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **2100** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **2100** may be a part of or associated with a power receiver. The power transfer system **2100** may comprise a housing defined by a top surface **2101**, a bottom surface (not shown), and sidewalls **2103**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **2101** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **2103** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **2107** may be disposed within a space defined between the top surface **2101**, sidewalls **2103**, and the bottom surface **2102**. In some embodiments, the power transfer system **2100** may not include a housing and the substrate **2107** may include the top surface **2101**, sidewalls **2103**, and the bottom surface **2102**. The substrate **2107** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may transmit radiation, and may act as thin reflectors.

An antenna **2104** may be constructed on or below the top surface **2101**. When the power transfer system **2100** is a part of or associated with a power transmitter, the antenna **2104** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **2100** is a part of or associated with a power receiver, the antenna **2104** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **2100** may operate as a transceiver and the antenna **2104** may both transmit and receive electromagnetic waves. The antenna **2104** may be constructed from materials such as metals, alloys, and composites. For example, the antenna **2104** may be made of copper or copper alloys. The antenna **2104** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **2100** shown in FIG. **21**, the antenna **2104** is constructed in a shape of a monopole. A via **2105** may carry a power feed line (not shown) to the antenna **2104**. The power feed line may provide current to the antenna **2104**.

The power transfer system **2100** may include a ground plane (not shown) at or above the bottom surface. The ground plane may be formed by materials such as metal, alloys, and composites. In an embodiment, the ground plane may be formed by copper or a copper alloy. In some embodiments, the ground plane may be constructed of a solid sheet of material. In other embodiments, the ground plane may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. The via **2105** carrying the power feed line to the antenna **2104** may pass through the ground plane. In some embodiments, the ground plane may be electrically connected to the antenna. In some embodiments, the ground plane may not be electrically connected to the antenna **2104**. For such implementations, an insulation area to insulate the via **2105** from the ground plane may be constructed between the via **2105** and the ground plane. In some embodiments, the ground plane may act as a reflector of the electromagnetic waves generated by the antenna **2104**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **2100** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antenna **2104** from or towards the top surface **2101**. Therefore, there may be no leakage of electromagnetic power from the bottom surface.

FIG. **22** schematically illustrates a top perspective view of an exemplary near-field power transfer system **2200**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **2200** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **2200** may be a part of or associated with a power receiver. The power transfer system **2200** may comprise a housing defined by a top surface **2201**, a bottom surface (not shown), and sidewalls **2203**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **2201** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **2203** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **2207** may be disposed within a space defined between the top surface **2201**, sidewalls **2203**, and the bottom surface **2202**. In some embodiments, the power transfer system **2200** may not include a housing and the substrate **2207** may include the top surface **2201**, sidewalls **2203**, and the bottom surface **2202**. The substrate **2207** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may transmit radiation, and may act as thin reflectors.

An antenna **2204** may be constructed on or below the top surface **2201**. When the power transfer system **2200** is a part of or associated with a power transmitter, the antenna **2204** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **2200** is a part of or associated with a power receiver, the antenna **2204** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **2200** may operate as a transceiver and the antenna **2204** may both transmit and receive electromagnetic waves. The antenna **2204** may be constructed from materials such as metals, alloys, and composites. For example, the antenna **2204** may be made of copper or copper alloys. A via **2205** may carry a power feed line (not shown) to the antenna. The power feed line may provide current to the antenna **2204**. The antenna **2204** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **2200** shown in FIG. **22**, the antenna **2204** is constructed in a shape of a monopole including antenna segments **2210** placed close to each other. The currents flowing through the neighboring antenna segments **2210** may be in opposite directions. For example, if the current in the antenna segment **2210***b* is flowing from left to right of FIG. **22**, the current each of the antenna segments **2210***a*, **2210***c* may be flowing from right to left. The opposite flow of the current results in mutual cancellation of the electromagnetic radiation in the far field of the power transfer system **2200**. Therefore, there may be no transfer of power in the far field of the power transfer system **2200**. Such cancellation, however, may not occur in a near-field active zone of the power transfer system **2200**, where the transfer of power may occur. One ordinarily skilled in the art will appreciate the cancellation of electromagnetic radiation in the far field and absence of such cancellation in the near-field is dictated by one or more solutions of Maxwell's equations for time-varying electric and magnetic fields generated by the currents flowing in opposite directions. One ordinarily skilled in the art should further appreciate the near field active zone is defined by the presence of electromagnetic power in the immediate vicinity of the power transfer system **2200**. The power transfer system **2200** may include a ground plane (not shown) at or above the bottom surface. The ground plane may be formed by materials such as metal, alloys, and composites. In an embodiment, the ground plane may be formed by copper or a copper alloy. In some embodiments, the ground plane may be constructed of a solid sheet of material. In other embodiments, the ground plane may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. The via **2205** carrying the power feed line to the antenna **2204** may pass through the ground plane. In some embodiments, the ground plane may be electrically connected to the antenna. In some embodiments, the ground plane may not be electrically connected to the antenna **2204**. For such implementations, an insulation area to insulate the via **2205** from the ground plane may be constructed between the via **2205** and the ground plane. In some embodiments, the ground plane may act as a reflector of the electromagnetic waves generated by the antenna **2204**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **2200** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antenna **2204** from or towards the top surface **2201**. Therefore, there may be no leakage of electromagnetic power from the bottom surface.

FIG. **23** schematically illustrates a top perspective view of an exemplary near-field power transfer system **2300**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **2300** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **2300** may be a part of or associated with a power receiver. The power transfer system **2300** may comprise a housing defined by a top surface **2301**, a bottom surface (not shown), and sidewalls **2303**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **2301** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **2303** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **2307** may be disposed within a space defined between the top surface **2301**, sidewalls **2303**, and the bottom surface **2302**. In some embodiments, the power transfer system **2300** may not include a housing and the substrate **2307** may include the top surface **2301**, sidewalls **2303**, and the bottom surface **2302**. The substrate **2307** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may transmit radiation, and may act as thin reflectors.

An antenna **2304** may be constructed on or below the top surface **2301**. When the power transfer system **2300** is a part of or associated with a power transmitter, the antenna **2304** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **2300** is a part of or associated with a power receiver, the antenna **2304** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **2300** may operate as a transceiver and the antenna **2304** may both transmit and receive electromagnetic waves. The antenna **2304** may be constructed from materials such as metals, alloys, and composites. For example, the antenna **2304** may be made of copper or copper alloys. The antenna **2304** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **2300** shown in FIG. **23**, the antenna **2304** is constructed as a hybrid dipoles comprising a first spiral pole **2320***a* and a second spiral pole **2320***b*. A first power feed line supplying current to the first spiral pole **2320***a* may be provided through a first via **2305***a* and a second power feed supplying current the second spiral pole **2320***b* may be provided through a second via **2305***b*. The antenna segments in each of the spiral poles **2320** may mutually cancel the electromagnetic radiation in the far field generated by the spiral dipoles **2320** thereby reducing the transfer of power to the far field. For example, the antenna segments in the first spiral pole **2320***a* may cancel the far field electromagnetic radiation generated by each other. Additionally, or in the alternative, the far field radiation generated by one or more antenna segments of the first spiral pole **2320***a* may be cancelled by the far field radiation generated by one or more antenna segments of the second spiral pole **2320***b*. One ordinarily skilled in the art will appreciate the cancellation of electromagnetic radiation in the far field and absence of such cancellation in the near-field is dictated by one or more solutions of Maxwell's equations for time-varying electric and magnetic fields generated by the currents flowing in opposite directions.

The power transfer system **2300** may include a ground plane (not shown) at or above the bottom surface. The ground plane may be formed by materials such as metal, alloys, and composites. In an embodiment, the ground plane may be formed by copper or a copper alloy. In some embodiments, the ground plane may be constructed of a solid sheet of material. In other embodiments, the ground plane may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. The vias **2305** carrying the power feed lines to the antenna may pass through the ground plane. In some embodiments, the ground plane may be electrically connected to the antenna. In some embodiments, the ground plane may not be electrically connected to the antenna **2304**. For such implementations, an insulation area to insulate the vias **2305** from the ground plane may be constructed between the vias **2305** and the ground plane. In some embodiments, the ground plane may act as a reflector of the electromagnetic waves generated by the antenna **2304**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **2300** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antenna **2304** from or towards the top surface **2301**. Therefore, there may be no leakage of electromagnetic power from the bottom surface.

The hybrid antenna **2304** may be required for wideband and/or multiband designs. For example, a non-hybrid structure may be highly efficient at a first frequency and at a first distance between the transmitter and the receiver, but may be at inefficient other frequencies and distances. Incorporating more complex structure such as a hybrid antenna **2304** may allow for higher efficiencies along a range of frequencies and distances.

FIG. **24**A and FIG. **24**B schematically illustrate a top perspective view and a side perspective view respectively of an exemplary near-field power transfer system **2400**, according to an embodiment of the disclosure. In some embodiments, the power transfer system **2400** may be a part of or associated with a power transmitter. In other embodiments, the power transfer system **100** may be a part of or associated with a power receiver. The power transfer system **2400** may comprise a housing defined by a top surface **2401**, a bottom surface **2402**, and sidewalls **2403**. In some embodiments, the housing may be constructed of a material creating minimal obstructions for electromagnetic waves to pass through. In other embodiments, different portions of the housing may be constructed with materials having different electromagnetic properties such as permeability and permittivity. For example, the top surface **2401** may allow electromagnetic waves to pass through with minimal obstruction while the sidewalls **2403** may obstruct electromagnetic waves by attenuation, absorption, reflection, or other techniques known in the art.

A substrate **2407** may be disposed within a space defined between the top surface **2401**, sidewalls **2403**, and the bottom surface **2402**. In some embodiments, the power transfer system **2400** may not include a housing and the substrate **2407** may include the top surface **2401**, sidewalls **2403**, and the bottom surface **2402**. The substrate **2407** may comprise any material capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. The metamaterials may be a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. The metamaterials disclosed herein may receive radiation or may transmit radiation, and may act as thin reflectors.

The power transfer system may include hierarchical antennas **2404** that may be constructed on or below the top surface **2401**. When the power transfer system **2400** is a part of or associated with a power transmitter, the antennas **2404** may be used for transmitting electromagnetic waves. Alternatively, when the power transfer system **2400** is a part of or associated with a power receiver, the antennas **2404** may be used for receiving electromagnetic waves. In some embodiments, the power transfer system **2400** may operate as a transceiver and the antennas **2404** may both transmit and receive electromagnetic waves. The antennas **2404** may be constructed from materials such as metals, alloys, and composites. For example, the antennas **2404** may be made of copper or copper alloys. The antennas **2404** may be constructed to have different shapes based on the power transfer requirements. In the exemplary system **2400** shown in FIG. **24**A and FIG. **24**B, the antennas **2404** are constructed in a hierarchical spiral structure with a level zero hierarchical antenna **2404***a* and a level one hierarchical antenna **2404***b*. Each of the hierarchical antennas **2404** may include antenna segments, wherein antenna segments have currents flowing in the opposite directions to cancel out the far field radiations. For example, the antenna segments in the level zero hierarchical antenna **2404***a* may cancel the far field electromagnetic radiation generated by each other. Additionally, or in the alternative, the far field radiation generated by one or more antenna segments of the level zero hierarchical antenna **2404***a* may be cancelled by the far field radiation generated by one or more antenna segments of the level one hierarchical antenna **2404***b*. A power feed line (not shown) to the antennas is carried through a via **2405**. The power feed line may supply current to the antenna **2404**.

The power transfer system **2400** may include a ground plane **2406** at or above the bottom surface **2402**. The ground plane **2406** may be formed by materials such as metal, alloys, and composites. In an embodiment, the ground plane **2406** may be formed by copper or a copper alloy. In some embodiments, the ground plane **2406** may be constructed of a solid sheet of material. In other embodiments, the ground plane **2406** may be constructed using material strips arranged in shapes such as loops, spirals, and meshes. The via **2405** carrying a power feed line to the antenna may pass through the ground plane **2406**. In some embodiments, the ground plane **2406** may be electrically connected to one or more of the antennas **2404**. In some embodiments, the ground plane **2406** may not be electrically connected to the antennas **2404**. For such implementations, an insulation area **2408** to insulate the via **2405** from the ground plane **2406** may be constructed between the via **2405** and the ground plane **2406**. In some embodiments, the ground plane **2406** may act as a reflector of the electromagnetic waves generated by the antennas **2404**. In other words, the ground plane may not allow electromagnetic transmission beyond the bottom surface of the power transfer system **2400** by cancelling and/or reflecting the transmission image formed beyond the bottom surface. Reflecting the electromagnetic waves by the ground plane may reinforce the electromagnetic waves transmitted by the antennas **2404** from or towards the top surface **2401**. Therefore, there may be no leakage of electromagnetic power from the bottom surface **2402**. In some embodiments, there may be multiple ground planes, with a ground plane for each of the hierarchical antennas **2404**. In some embodiments, the hierarchical antennas have different power feed lines carried through multiple vias.

The hierarchical antennas **2404** may be required for wideband and/or multiband designs. For example, a non-hierarchical structure may be highly efficient at a first frequency and at a first distance between the transmitter and the receiver, but may be inefficient at other frequencies and distances. Incorporating more complex structures, such as hierarchical antennas **2404**, may allow for higher efficiencies along a range of frequencies and distances.

FIGS. **25**A-**25**H illustrate various views of a representative near-field antenna **2500** in accordance with some embodiments. It is noted that the representative near-field antenna **2500**, and its various components, may not be drawn to scale. Moreover, while some example features are illustrated, various other features have not been illustrated for the sake of brevity and so as not to obscure pertinent aspects of the example implementations disclosed herein. In some instances, the near-field antenna **2500** is referred to as a "quad-pol antenna element." In some embodiments, the near-field antenna **2500** is part of the charging pad **100**, e.g., one or more of the near-field antennas **2500** are included in each of the antenna zones **290** (FIG. **1**B). In some embodiments, the near-field antennas **2500** are the only antennas included in each of the antenna zones while, in other embodiments, the near-field antennas **2500** can be included in respective antenna zones along with other antennas described herein. In still other embodiments, the near-field antennas **2500** can be included as the only antennas in certain of the antenna zones, while other antenna zones may include only other types of antennas that are described herein.

FIG. **25**A shows an isometric view of the near-field antenna **2500** in accordance with some embodiments. As shown, the near-field antenna **2500** includes a substrate **2506** offset from a reflector **2504** (e.g., offset along the z-axis), and thus a gap is formed between the reflector **2504** and substrate **2506**. In such an arrangement, the reflector **2504** defines a first plane (e.g., a first horizontal plane: the bottom surface) and the substrate **2506** defines a second plane (e.g., a second horizontal plane: the top surface) that is offset from the first plane. In some embodiments, the substrate **2506** is made from a dielectric, while in other embodiments the substrate **2506** is made from other materials capable of insulating, reflecting, absorbing, or otherwise housing electrical lines conducting current, such as metamaterials. Metamaterials are a broad class of synthetic materials that are engineered to yield desirable magnetic permeability and electrical permittivity. At least one of the magnetic permeability and electrical permittivity may be based upon power-transfer requirements, and/or compliance constraints for government regulations. In various embodiments, the metamaterials disclosed herein can be used to receive radiation, transmit radiation, and/or as reflectors.

In some embodiments, the reflector **2504** is a metal sheet (e.g., copper, copper alloy, or the like) while in other embodiments the reflector **2504** is a metamaterial. The reflector **2504** is configured to reflect some electromagnetic signals radiated by the near-field antenna **2500**. In other words, the reflector **2504** may not allow electromagnetic transmission beyond the bottom surface of the near-field antenna **2500** by reflecting the electromagnetic signals radiated by the near-field antenna **2500**. Additionally, reflecting the electromagnetic signals by the reflector **2504** can redirect some of the electromagnetic signals transmitted by antenna elements of the near-field antenna **2500** from or towards the substrate **2506**. In some instances, the reflector **2504** reduces far-field gain of the near-field antenna **2500**. In some embodiments, the reflector **2504** also cancels some electromagnetic signals radiated by the near-field antenna **2500**.

The substrate **2506** further includes four distinct coplanar antenna elements (also referred to herein as "radiating elements"), where each of the four distinct antenna elements follows a respective meandering pattern. The four distinct coplanar antenna elements may each occupy a distinct quadrant of the substrate. The coplanar antenna elements may be embedded in the substrate **2506**, such that respective first surfaces of the coplanar antenna elements are coplanar with a top surface of the substrate **2506**, and respective second surfaces, opposite the respective first surfaces, of the coplanar antenna elements are coplanar with a bottom surface of the substrate **2506**. The respective meandering patterns are used to increase an effective length of each of the four distinct coplanar antenna elements, thus resulting in a lower resonant frequency of the antenna **2500** while reducing an overall size of the antenna **2500**.

In some embodiments, the respective meandering patterns are all the same while, in other embodiments, one or more of the respective meandering patterns differ. Each of the four distinct coplanar antenna elements includes a plurality of continuous (and/or contiguous) segments, which are discussed below with reference to FIG. **25**F. In some embodiments (not shown), a shape of each segment in the plurality of segments is substantially the same (e.g., each is rectangular or some other shape). Alternatively, in some other embodiments, a shape of at least one segment in the plurality of segments differs from shapes of other segments in the plurality of segments. It is noted that various combinations of shapes can be used to form the segments of a respective antenna element, and the shapes shown in FIG. **25**A are merely illustrative examples. Further, in some embodiments, the substrate **2506** is not included and the four distinct coplanar antenna elements are made from stamped metal (i.e., the radiating elements are sitting in open space above the reflector **2504**).

The four distinct coplanar antenna elements are shown in FIG. **25**A as a first radiating element **2502**-A, a second radiating element **2502**-B, a third radiating element **2502**-C, and a fourth radiating element **2502**-D. The first radiating element **2502**-A and the second radiating element **2502**-B together compose (i.e., form) a first dipole antenna **2501**-A positioned along (e.g., center on) a first axis (e.g., the X-axis). In other words, the first radiating element **2502**-A is a first pole of the first dipole antenna **2501**-A and the second radiating element **2502**-B is a second pole of the first dipole antenna **2501**-A. The first dipole antenna **2501**-A is indicated by the dashed line.

In addition, the third radiating element **2502**-C and the fourth radiating element **2502**-D together compose (i.e., form) a second dipole antenna **2501**-B positioned along a second axis (e.g., the Y-axis) perpendicular to the first axis. In other words, the third radiating element **2502**-C is a first pole of the second dipole antenna **2501**-B and the fourth radiating element **2502**-D is a second pole of the second dipole antenna **2501**-B. The second dipole antenna **2501**-B is indicated by the dashed-dotted line.

FIG. **25**B shows another isometric view (e.g., isometric underneath view) of the near-field antenna **2500** in accordance with some embodiments. For ease of illustration, the reflector **2504** is not shown in FIG. **25**B.

As shown, the near-field antenna **2500** further includes a first feed **2508**-A and a second feed **2508**-B attached to a central region of the substrate **2504**. The first feed **2508**-A is connected to the first and second radiating elements **2502**-A, **2502**-B forming the first dipole antenna **2501**-A. More specifically, the first feed **2508**-A is connected to the second radiating element **2502**-B via a connector **2512**-A (FIG. **25**C) and to the first radiating element **2502**-A via an intra-dipole connector **2510**-A. The first feed **2508**-A is configured to supply electromagnetic signals that originate from a power amplifier (e.g., power amplifier **108**, FIG. **26**) to the first and second radiating elements **2502**-A, **2502**-B.

The second feed **2508**-B is connected to the third and fourth radiating elements **2502**-C, **2502**-D forming the second dipole antenna **2501**-B. More specifically, the second feed **2508**-B is connected to the fourth radiating element **2502**-D via a connector **2512**-B (FIG. **25**C) and to the third radiating element **2502**-C via an intra-dipole connector **2510**-B. The second feed **2508**-B is configured to supply electromagnetic signals that originate from the power amplifier to the third and fourth radiating elements **2502**-C, **2502**-D. The four radiating elements are configured to radiate the provided electromagnetic signals (e.g., radio frequency power waves), which are used to power or charge a wireless-power-receiving device.

In some embodiments, as explained below in detail, the four radiating elements do not radiate at the same time. Instead, based on information about a wireless-power receiving device, either the first dipole antenna **2501**-A is supplied the electromagnetic signals or the second dipole antenna **2501**-B is supplied electromagnetic signals.

The electromagnetic signals radiated by the first dipole antenna **2501**-A have a first polarization and the electromagnetic signals radiated by the second dipole antenna **2501**-B have a second polarization perpendicular to the first polarization. The differences in polarization are attributable, at least in part, to the orientations of the first and second dipole antennas **2501**-A, **2501**-B. For example, the first dipole antenna **2501**-A is positioned along the first axis (e.g., the X-axis) and the second dipole antenna **2501**-B is positioned along the second axis (e.g., the Y-axis), which is perpendicular to the first axis. Thus, in some instances, the electromagnetic signals are fed to the dipole antenna whose polarization matches a polarization of a power-receiving-antenna of a wireless-power-receiving device. A process for selectively coupling one of the dipole antennas to an electromagnetic signals feeding source (i.e., a power amplifier **108**) is described below in method **3000** (FIG. **30**).

For ease of discussion below, the substrate **2506** and the radiating elements **2502**-A-**2502**-D are referred to collectively as the "radiator **2507**" when appropriate.

FIGS. **25**C-**25**D show different side views of the near-field antenna **2500**, where the side view in FIG. **25**D is rotated 90 degrees relative to the side view in FIG. **25**C. In certain embodiments or circumstances, the first feed **2508**-A is connected to the second radiating element **2502**-B by the connector **2512**-A and to the first radiating element **2502**-A by the intra-dipole connector **2510**-A (FIG. **25**B also shows the intra-dipole connector **2510**-A). In certain embodiments or circumstances, the second feed **2508**-B is connected to the fourth radiating element **2502**-B by the connector **2512**-B and to the third radiating element **2502**-C by the intra-dipole connector **2510**-B (FIG. **25**B also shows the intra-dipole connector **2510**-B).

FIG. **25**E shows another side view of the near-field antenna **2500** in accordance with some embodiments. As shown, the first and second feeds **2508**-A, **2508**-B are substantially perpendicular to the radiator **2507**. For example, each of the feeds **2508**-A, **2508**-B is disposed along a respective vertical axis while the antenna **2507** is disposed along a horizontal axis/plane. Further, the first and second feeds **2508**-A, **2508**-B are connected at a first end to the antenna **2507**, and are connected at a second end, opposite the first end, to a printed circuit board **2514** and a ground plane **2516**. In some embodiments, the printed circuit board **2514** and the ground plate **2516** compose the reflector **2504**. Alternatively, in some embodiments, the reflector **2504** is a distinct component, which is offset from the printed circuit board **2514** and the ground plane **2516** (e.g., positioned between the antenna **2507** and the printed circuit board **2514**). In this arrangement, the reflector **2504** may define openings (not shown), and the first and second feeds **2508**-A, **2508**-B may pass through said openings.

As shown in the magnified view **2520**, the first feed **2508**-A includes a feedline **2524**-A (e.g., a conductive metal line) housed (i.e., surrounded) by a shield **2522**-A. The feedline **2524**-A is connected to metal traces (e.g., communication buses **208**, FIG. **26**) of the printed circuit board **2514** by a metal deposit **2526**-A. Further, the shield **2522**-A contacts the ground plane **2516**, thereby grounding the first dipole **2501**-A.

Similarly, the second feed **2508**-B includes a feedline **2524**-B housed by a shield **2522**-B. The feedline **2524**-B is connected to metal traces (not shown) of the printed circuit board **2514** by a metal deposit **2526**-B. Further, the shield **2522**-B contacts the ground plane **2516**, thereby grounding the second dipole **2501**-B. As explained below with reference to FIG. **26**, the metal traces of the printed circuit board **2514** may be connected to one or more additional components (not shown in FIGS. **25**A-**25**H) of the near-field antenna **2500**, including one or more power amplifiers **108**, an impedance-adjusting component **2620**, and a switch **2630** (also referred to herein as "switch circuitry").

Although not shown in FIG. **25**E, a dielectric may separate the feedline from the shield in each feed (e.g., electrically isolate the two components). Additionally, another dielectric can surround the shield in each feed to protect the shield (i.e., the first and second feeds **2508**-A, **2508**-B may be coaxial cables). It is also noted that the particular shapes of the metal deposits **2526**-A, **2526**-B can vary in certain embodiments, and the shapes shown in FIG. **25**E are examples used for ease of illustration.

FIG. **25**F shows a representative radiating element **2550** following a meandering pattern in accordance with some embodiments. As shown, the representative radiating element **2550** includes: (i) a first plurality of segments **2560**-A-**2560**-D, and (ii) a second plurality of segments **2562**-A-**2562**-C interspersed between the first plurality of segments **2560**-A-**2560**-D (separated by dashed lines). In some embodiments, the first plurality of segments **2560**-A-**2560**-D and the second plurality of segments **2562**-A-**2562**-C are continuous segments. Alternatively, in some other embodiments, the first plurality of segments **2560**-A-**2560**-D and the second plurality of segments **2562**-A-**2562**-C are contiguous segments (e.g., ends of neighboring segments abut one another). The illustrated boundaries (e.g., the dashed lines) separating the segments in FIG. **25**F are merely one example set of boundaries that is used for illustrative purposes only, and one of skill in the art will appreciate (upon reading this disclosure) that other boundaries (and segment delineations) are within the scope of this disclosure.

As shown, lengths of segments in the first plurality of segments **2560**-A-**2560**-D increase from a first end portion **2564** of the radiating element **2550** to a second end portion **2566** of the radiating element **2550**. In some embodiments, while not shown, lengths of segments in the second plurality of segments **2562**-A-**2562**-C increase from the first end portion **2564** of the radiating element **2550** to the second end portion **2566** of the radiating element **2550**. Alternatively, in some other embodiments, lengths of segments in the second plurality of segments **2562**-A-**2562**-C remain substantially the same from the first end portion **2564** of the radiating element **2550** to the second end portion **2566** of the radiating element **2550**. In the illustrated embodiment, the lengths of the first plurality of segments **2560**-A-**2560**-D are different from the lengths of the second plurality of segments **2562**-A-**2562**-C. Further, the lengths of the first plurality of segments **2560**-A-**2560**-D toward the second end portion **2566** of the radiating element **2550** are greater than the lengths of the second plurality of segments **2562**-A-**2562**-C toward the second end portion **2566** of the radiating element **2550**.

In some embodiments, the shape of the radiating element provides certain important advantages. For example, the specific shape of the representative radiating element **2550** shown in FIG. **25**F provides the following advantages: (i) the shape allows two perpendicularly-positioned dipoles to fit in a small area and occupy four quadrants of the substrate **2506** where each pair of quadrants is perpendicular to each other, and (ii) the width and gaps between segments of neighboring radiating elements (i.e., spacing between quadrants) can be varied to tune the near-field antenna **2500** to a desired frequency, while still maintaining the radiating elements' miniaturized form-factor. To illustrate numeral (i), with reference to FIG. **25**A, the first and second radiating elements **2502**-A, **2502**-B occupy a first pair of quadrants that include sides of the near-field antenna that are along the Y-axis. Further, the third and fourth radiating elements **2502**-C, **2502**-D occupy a second pair of quadrants that include sides of the near-field antenna that are along the X-axis. Accordingly, the first and second pairs of quadrants of the substrate **2506** include sides of the NF antenna that are perpendicular to each other (e.g., this feature is facilitated, in part, by a width of each radiating element increasing from a central portion of the near-field antenna **2500** to a respective side of the near-field antenna **2500**).

FIG. **25**G shows a top view of the representative near-field antenna **2500** in accordance with some embodiments. Dimensions of the near-field antenna **2500** can effect an operating frequency of the near-field antenna **2500**, radiation efficiency of the near-field antenna **2500**, and a resulting radiation pattern (e.g., radiation pattern **2800**, FIG. **28**A) produced by the near-field antenna **2500**, among other characteristics of the NF antenna **2500**. As one example, the near-field antenna **2500**, when operating at approximately 918 MHz has the following dimensions (approximately): D1=9.3 mm, D2=12.7 mm, D3=23.7 mm, D4=27 mm, D5=32 mm, D6=37.5 mm, D7=10.6 mm, D8=5.1 mm, D9=10.6 mm, D10=5.5 mm, D11=2.1 mm, and D12=28 mm. Further, the reflector **2504** may have a width of 65 mm, a height of 65 mm, and a thickness of 0.25 mm.

FIG. **25**H shows another top view of the representative near-field antenna **2500** in accordance with some embodiments. As shown, the four distinct coplanar antenna elements each occupy a distinct quadrant of the substrate **2506** (e.g., occupy one of the quadrants **2570**-A through **2570**-D, demarcated by the dash-dotted lines). Further, (i) a first end portion **2564** of the respective meandering pattern followed by each of the four distinct antenna elements borders a central portion **2574** (dotted line) of the near-field antenna **2500**, and (ii) a second end portion **2566** of the respective meandering pattern followed by each of the four distinct antenna elements borders one of the edges **2572**-A-**2572**-D of the near-field antenna **2500**. In such an arrangement, a longest dimension of the respective meandering pattern followed by each of the four distinct antenna elements (e.g., segment **2560**-D) is closer to a distinct edge **2572** of the near-field antenna than to the central portion **2574** of the near-field antenna **2500**. Moreover, a shortest dimension of the respective meandering pattern followed by each of the four distinct antenna elements is closer to the central portion **2574** of the near-field antenna **2500** than a distinct edge **2572** of the near-field antenna **2500**. Thus, a width of each of the four distinct antenna elements increases, in a meandering fashion, from the central portion **2574** of the near-field antenna **2500** to a respective edge **2572** of the near-field antenna **2500**. Furthermore, in some embodiments, the longest dimension of the respective meandering pattern parallels the distinct edge **2572**.

As shown in FIG. **27**, the near-field antenna **2500** (when it includes a reflector) creates substantially uniform radiation pattern **2700** that has minimal far-field gain. The dimensions provided above are merely used for illustrative purposes, and a person of skill in the art (upon reading this disclosure) will appreciate that various other dimensions could be used to obtain acceptable radiation properties, depending on the circumstances.

FIG. **26** is a block diagram of a control system **2600** used for controlling operation of certain components of the near-field antenna **2500** in accordance with some embodiments. The control system **2600** may be an example of the charging pad **100** (FIG. **1**A), however, one or more components included in the charging pad **100** are not included in the control system **2600** for ease of discussion and illustration.

The control system **2600** includes an RF power transmitter integrated circuit **160**, one or more power amplifiers **108**, an impedance-adjusting component **2620**, and the near-field antenna **2500**, which includes the first and second dipole antennas **2501**-A, **2501**-B. Each of these components is described in detail above, and the impedance-adjusting component **2620** is described in more detail below.

The impedance-adjusting component **2620** may be an RF termination or load, and is configured to adjust an impedance of at least one of the first and second dipole antennas **2501**-A, **2501**-B. Put another way, the impedance-adjusting component **2620** is configured to change an impedance one of the dipole antennas, thereby creating an impedance mismatch between the two dipole antennas. By creating an impedance mismatch between the two dipole antenna, mutual coupling between the two dipole antennas is substantially reduced. It is noted that the impedance-adjusting component **2620** is one example of an antenna-adjusting component. Various other antenna-adjusting components might be used (e.g., to change an effective length of any of the radiating elements) to adjust various other characteristics of the antenna (e.g., such as length of the respective antenna elements of each dipole), in order to ensure that one of the two dipoles is not tuned to a transmission frequency of the other dipole.

The control system **2600** also includes a switch **2630** (also referred to herein as "switch circuitry") having one or more switches therein (not shown). The switch **2630** is configured to switchably couple the first and second dipole antennas **2501**-A, **2501**-B to the impedance-adjusting component **2620** and at least one power amplifier **108**, respectively (or vice versa), in response to receiving one or more instructions in the form of electrical signals (e.g., the "Control Out" signal) from the RF power transmitter integrated circuit **160**. For example, the switch **2630** may couple, via one or more switches, the first dipole antenna **2501**-A with the impedance-adjusting component **2620** and the second dipole antenna **2501**-B with at least one power amplifier **108**, or vice versa.

To accomplish the switching discussed above, the switch **2630** provides distinct signal pathways (e.g., via the one or more switches therein) to the first and second dipole antennas **2501**-A, **2501**-B. Each of the switches, once closed, creates a unique pathway between either: (i) a respective power amplifier **108** (or multiple power amplifiers **108**) and a respective dipole antenna, or (ii) the impedance-adjusting component **2620** and a respective dipole antenna. Put another way, some of the unique pathways through the switch **2630** are used to selectively provide RF signals to one of the dipole antennas **2501**-A, **2501**-B while some of the unique pathways through the switch **2630** are used to adjust an impedance of one of the dipole antennas **2501**-A, **2501**-B (i.e., detune the dipole antennas **2501**-A, **2501**-B). It is noted that two or more switches of the switch circuitry may be closed at the same time, thereby creating multiple unique pathways to the near-field antenna **2500** that may be used simultaneously.

As shown, the RF power transmitter integrated circuit **160** is coupled to the switch **2630** via busing **208**. The integrated circuit **160** is configured to control operation of the one or more switches therein (illustrated as the "Control Out" signal in FIGS. **1**A, **1**C, and **26**). For example, the RF power transmitter integrated circuit **160** may close a first switch in the switch **2630**, which connects a respective power amplifier **108** with the first dipole antenna **2501**-A, and may close a second switch in the switch **2630** that connects the impedance-adjusting component **2620** with the second dipole antenna **2501**-B, or vice versa. Moreover, the RF power transmitter integrated circuit **160** is coupled to the one or more power amplifiers **108** and is configured to cause generation of a suitable RF signal (e.g., the "RF Out" signal) and cause provision of the RF signal to the one or more power amplifiers **108**. The one or more power amplifiers **108**, in turn, are configured to provide the RF signal (e.g., based on an instruction received from the RF power transmitter integrated circuit **160**) to one of the dipole antennas via the switch **2630**, depending on which switch (or switches) in the switch circuitry **2630** is (are) closed.

In some embodiments, the RF power transmitter integrated circuit **160** controller is configured to control operation of the switch **2630** and the one or more power amplifiers **108** based on one or more of: (i) a location of a wireless-power-receiving device near (or on) the near-field antenna **2500**, (ii) a polarization of a power-receiving-antenna of the wireless-power-receiving device, and (iii) a spatial orientation of the wireless-power-receiving device. In some embodiments, the RF power transmitter integrated circuit **160** receives information that allows the circuit **160** to determine (i) the location of the wireless-power-receiving device, (ii) the polarization of the power-receiving-antenna of the wireless-power-receiving device, and (iii) the spatial orientation of the wireless-power-receiving device from the wireless-power-receiving device. For example, the wireless-power-receiving device can send one or more communications signals to a communication radio of the near-field antenna **2500** indicating each of the above (e.g., data in the one or more communications signals indicates the location, polarization, and/or orientation of the wireless-power-receiving device). Further, as shown in FIG. **1**A, the wireless communication component **204** (i.e., the communication radio of the near-field antenna **2500**) is connected to the RF power transmitter integrated circuit **160**. Thus, the data received by the wireless communication component **204** can be conveyed to the RF power transmitter integrated circuit **160**.

In some embodiments, the first dipole antenna **2501**-A may be configured to radiate electromagnetic signals having a first polarization (e.g., horizontally polarized electromagnetic signals) and the second dipole antenna **2501**-B may be configured to radiate electromagnetic signals having a second polarization (e.g., vertically polarized electromagnetic signals) (or vice versa). Further, if the power-receiving-antenna of the wireless-power-receiving device is configured to receive electromagnetic signals having the first polarization, then the RF power transmitter integrated circuit **160** will connect the first dipole antenna **2501**-A to the one or more power amplifiers **108** and will connect the impedance-adjusting component **2620** with the second dipole antenna **2501**-B, via the switch **2630**. In this way, the electromagnetic signals radiated by the near-field antenna **2500** will have a polarization that matches the polarization of the target device, thereby increasing an efficiency of energy transferred to the wireless-power-receiving device.

In some embodiments, the switch **2630** may be part of (e.g., internal to) the near-field antenna **2500**. Alternatively, in some embodiments, the switch **2630** is separate from the near-field antenna **2500** (e.g., the switch **2630** may be a distinct component, or may be part of another component, such as the power amplifier(s) **108**). It is noted that any switch design capable of accomplishing the above may be used.

FIG. **27** shows a radiation pattern **2700** generated by the near-field antenna **2500** when it does include the back reflector **2504** (i.e., the radiating antenna elements are "backed" by the metallic reflector). The illustrated radiation pattern **2700** is generated by the near-field antenna **2500** when (i) the first dipole antenna **2501**-A is fed electromagnetic signals by the one or more power amplifiers **108**, and (ii) the near-field antenna **2500** includes the reflector **2504**. As shown, the radiation pattern **2700** has a higher concentration of EM energy produced along the X-axis and Y-axis (and has a radiation null along the Z-axis) and forms an overall torus shape. As such, the electromagnetic field concentration stays closer to the NF antenna **2500** and far-field gain is minimized (e.g., the EM field concentration stays closer to the radiator **2507** and the reflector **2504**, FIG. **25**E). Although not shown, the radiation pattern **2700** is polarized in a direction that is aligned with the X-axis.

Thus, by incorporating the reflector **2504**, the radiation pattern **2700** is rotated 90 degrees about the X-axis relative to the radiation pattern **2800** (FIG. **28**A, discussed below). Additionally, by incorporating the reflector **2504**, a radiation null is formed along the Z-axis, which substantially reduces far-field gain, and energy radiated by the near-field antenna **2500** is concentrated within a near-field distance from the near-field antenna **2500**. Again, the second dipole antenna **2501**-B may be connected to the impedance-adjusting component **2620** when the first dipole antenna **2501**-A is fed the electromagnetic signals.

FIG. **28**A to FIG. **28**C show various radiation patterns generated by an embodiment of the near-field antenna **2500** that does not include the reflector **2504**. The radiation pattern **2800** illustrated in FIG. **28**A is generated by the near-field antenna **2500** when the first dipole antenna **2501**-A is fed electromagnetic signals by the one or more power amplifiers **108**. As shown, the radiation pattern **2800** has a higher concentration of EM energy produced along the Z-axis and the X-axis (and has a radiation null along the Y-axis) and forms an overall torus shape. This pattern **2800** shows that an antenna element, without the reflector, radiates outward/perpendicular to the near-field antenna **2500**. Although not shown, the radiation pattern **2800** is polarized in a first direction (e.g., aligned with the X-axis). Furthermore, the second dipole antenna **2501**-B may be connected to the impedance-adjusting component **2620** when the first dipole antenna **2501**-A is fed the electromagnetic signals by the one or more power amplifiers **108**.

The radiation pattern **2810** illustrated in FIG. **28**B is generated by the near-field antenna **2500** when the second dipole antenna **2501**-B is fed electromagnetic signals by the one or more power amplifiers **108** (i.e., the first dipole antenna **2501**-A is not fed electromagnetic signals and instead may be connected to the impedance-adjusting component **2620**). FIG. **28**B shows that the radiation pattern **2810** that has a higher concentration of EM energy produced along the Z-axis and the Y-axis (and has a radiation null along the X-axis), which also forms an overall torus shape. Although not shown, the radiation pattern **2810** is polarized in a second direction (e.g., aligned with the Y-axis). Accordingly, the first dipole antenna **2501**-A is configured to generate a radiation pattern **2800** polarized in the first direction while the second dipole antenna **2501**-B is configured to generate a radiation pattern **2810** polarized in the second direction perpendicular to the first direction. In this way, the first dipole antenna **2501**-A is fed when the polarization of the electromagnetic signals generated by the first dipole antenna **2501**-A match a polarization of a power-receiving antenna of a wireless-power-receiving device. Alternatively, the second dipole antenna **2501**-D is fed when the polarization of the electromagnetic signals generated by the second dipole antenna **2501**-B match a polarization of a power-receiving antenna of a wireless-power-receiving device.

FIG. **28**C shows a radiation pattern **2820** generated when both the first and second dipole antennas are fed electromagnetic signals by the one or more power amplifiers **108**, and neither dipole antenna is connected to the impedance-adjusting component **2620**. As shown, the radiation pattern **2820** has higher concentrations of EM energy produced along the Z-axis, X-axis and the Y-axis (and a radiation null is formed between the X-axis and the Y-axis) and forms an overall torus shape.

FIGS. **29**A and **29**B show concentrations of energy radiated and absorbed by dipole antennas of the near-field antenna **2500** in accordance with some embodiments.

In particular, FIG. **29**A shows the resulting concentrations of energy radiated and absorbed by the dipole antennas **2501**-A, **2501**-B when an impedance of the first dipole antenna **2501**-A substantially matches an impedance of the second dipole antenna **2501**-B. FIG. **29**B shows the resulting concentrations of energy radiated and absorbed by the dipole antennas **2501**-A, **2501**-B of the near-field antenna **2500** when an impedance of the first dipole antenna **2501**-A differs from an impedance of the second dipole antenna **2501**-B, which is achieved by connecting one of the dipole antennas to the impedance-adjusting component **2620**. Put another way, the first and second dipole antennas **2501**-A, **2501**-B are intentionally detuned as a result of one of the dipole antennas being connected to the impedance-adjusting component **2620**.

An absence of an impedance mismatch between neighboring antenna elements leads to substantial mutual coupling between neighboring antenna elements. "Mutual coupling" refers to energy being absorbed by one antenna element (or one antenna dipole) when another nearby antenna element (or antenna dipole) is radiating. Antennas (or antenna arrays) with closely spaced antenna elements typically suffer from undesired mutual coupling between neighboring antenna elements, which limits the antenna's ability to radiate efficiently (this problem is particularly acute when the antenna elements are placed close together and when the antenna elements are miniaturized).

For example, with reference to FIG. **29**A, the second dipole antenna **2501**-B is fed electromagnetic signals by the one or more power amplifiers **108**, and the coloring along the second dipole antenna **2501**-B represents different concentrations of energy radiated by the second dipole antenna **2501**-B, with reds corresponding to high concentrations, greens corresponding to medium concentrations, and blues corresponding to low concentrations. The first dipole antenna **2501**-A in FIG. **29**A is not independently radiating, however, certain amounts of the energy radiated by the second dipole antenna **2501**-B is absorbed at the first dipole antenna **2501**-A as a result of the mutual coupling between the two dipole antennas. Because of this mutual coupling, a radiation efficiency of the near-field antenna **2500** is not optimized (e.g., the NF antenna **2500** may only be able to transfer 50% or less of the energy it attempts to transmit).

In contrast, with reference to FIG. **29**B, the second dipole antenna **2501**-B is fed electromagnetic signals by the one or more power amplifiers **108**. Additionally, the first dipole antenna **2501**-A is coupled to the impedance-adjusting component **2620**, thereby creating an intentional impedance mismatch between the two dipole antennas. In such a configuration, the first dipole antenna **2501**-A in FIG. **29**B is absorbing far less energy radiated by the second dipole antenna **2501**-B compared to an amount of the energy that the first dipole antenna **2501**-A was absorbing in FIG. **29**A. Accordingly, a radiation efficiency of the near-field antenna **2500** in FIG. **29**B is higher (e.g., the NF antenna **2500** may now be able to radiate 90% or greater of the energy it attempts to transmit) than the radiation efficiency of the near-field antenna **2500** in FIG. **29**A.

METHOD OF OPERATION

FIG. **30** is a flow diagram showing a method **3000** of wireless power transmission in accordance with some embodiments. Operations (e.g., steps) of the method **3000** may be performed by a controller (e.g., RF power transmitter integrated circuit **160**, FIGS. **1**A and **26**) associated with a near-field antenna (e.g., near-field antenna **2500**, FIG. **25**A). At least some of the operations shown in FIG. **30** correspond to instructions stored in a computer memory or computer-readable storage medium (e.g., memory **206** of the charging pad **100**, FIG. **2**A).

The method **3000** includes providing (**3002**) a near-field antenna that includes a reflector (e.g., reflector **2504**, FIG. **25**A) and four distinct coplanar antenna elements (e.g., radiating elements **2502**-A to **2502**-D, FIG. **25**A) offset from the reflector. The four distinct antenna elements follow respective meandering patterns, such as the meandering pattern shown in FIG. **25**F. Furthermore, (i) two antenna elements of the four coplanar antenna elements form a first dipole antenna (e.g., dipole antenna **2501**-A, FIG. **25**A) aligned with a first axis (e.g., X-axis, FIG. **25**A), and (ii) another two antenna elements (e.g., dipole antenna **2501**-B, FIG. **25**A) of the four coplanar antenna elements form a second dipole antenna aligned with a second axis (e.g., Y-axis, FIG. **25**A) perpendicular to the first axis. In some embodiments, the respective meandering patterns are all the same.

In some embodiments, a first antenna element (e.g., first radiating element **2502**-A) of the four distinct coplanar antenna elements is a first pole of the first dipole antenna and a second antenna element (e.g., second radiating element **2502**-B) of the four distinct coplanar antenna elements is a second pole of the first dipole antenna. Furthermore, a third antenna element (e.g., third radiating element **2502**-C) of the four distinct coplanar antenna elements may be a first pole of the second dipole antenna and a fourth antenna element (e.g., fourth radiating element **2502**-D) of the four distinct coplanar antenna elements may be a second pole of the second dipole antenna. The two antenna elements that form the first dipole antenna can each include two segments that are perpendicular to the first axis, and the other two antenna elements that form the second dipole antenna can each include two segments that parallel the first axis. For example, with reference to FIG. **25**A, the first and second radiating elements **2502**-A, **2502**-B each includes two segments (e.g., segments **2560**-C and **2560**-D, FIG. **25**F) that are perpendicular to the X-axis, and the third and fourth radiating elements **2502**-C, **2502**-D each includes two segments (e.g., segments **2560**-C and **2560**-D, FIG. **25**F) that are parallel to the X-axis. In such an arrangement, the two antenna elements that form the first dipole antenna are configured to radiate electromagnetic signals having a first polarization, and the two antenna elements that form the second dipole antenna are configured to radiate electromagnetic signals having a second polarization perpendicular to the first polarization.

In some embodiments, each of the four distinct antenna elements includes: (i) a first plurality of segments, and (ii) a second plurality of segments interspersed between each of the first plurality of segments. For example, with reference to FIG. **25**G, the second plurality of segments **2562**-A-**2562**-C are interspersed between the first plurality of segments **2560**-A-**2560**-D. In such embodiments, first lengths of segments in the first plurality of segments increase from a first end portion of the antenna element to a second end portion of the antenna element, as shown in FIGS. **25**F and **25**G. It is noted that the "first end portion" of each antenna element corresponds to the first end portion **2564** illustrated in FIG. **25**F, and the first end portion of each antenna element is near a central portion **2574** (FIG. **25**H) of the near-field antenna **2500**. Furthermore, the "second end portion" of each antenna element corresponds to the second end portion **2566** illustrated in FIG. **25**F, and the second end portion **2566** of each antenna element extends towards an edge **2572** (FIG. **25**H) of the near-field antenna **2500**. Thus, put simply, a width of each of the four distinct antenna elements increases, in a meandering fashion, from a central portion of the near-field antenna **2500** to a respective edge of the near-field antenna **2500**.

In some embodiments, second lengths of segments in the second plurality of segments also increase from the first end portion of the antenna element to the second end portion of the antenna element, while in other embodiments the second lengths of the segments in the second plurality of segments remain substantially the same, as shown in FIG. **25**F. Additionally, the first lengths of one or more segments in the first plurality of segments are different from the second lengths of the segments in the second plurality of segments. In some embodiments, the first lengths of the first plurality of segments toward the second end portion of the antenna element are greater than the second lengths of the second plurality of segments toward the second end portion of the antenna element. For example, the lengths of segments **2560**-C and **2560**-D are substantially longer than the lengths of segments **2562**-B and **2562**-C. Segments of the radiating elements are discussed in further detail above with reference to FIGS. **25**F and **25**G.

In some embodiments, a first end portion of the respective meandering pattern followed by each of the four distinct antenna elements borders a same central portion (e.g., central portion **2574**, FIG. **25**H) of the near-field antenna, and a second end portion of the respective meandering pattern followed by each of the four distinct antenna elements borders a distinct edge (e.g., one of the edges **2572**, FIG. **25**H) of the near-field antenna. Further, a longest dimension of the respective meandering pattern followed by each of the four distinct antenna elements may be closer to the distinct edge of the near-field antenna than to the same central portion of the near-field antenna. In addition, a shortest dimension of the respective meandering pattern followed by each of the four distinct antenna elements may be closer to the same central portion of the near-field antenna than the distinct edge of the near-field antenna.

In some embodiments, the four distinct coplanar antenna elements are formed on or within a substrate. For example, as shown in FIGS. **25**A and **25**B, opposing first and second surfaces of the four distinct coplanar antenna elements are exposed and coplanar with opposing first and second surfaces of the substrate **2506**. It is noted that a dielectric (e.g., thermoplastic or thermosetting polymer) can be deposited over the four distinct coplanar antenna elements so that the antenna elements are protected (may or may not be visible depending on the properties of the dielectric). In some embodiments, the substrate may include a metamaterial of a predetermined magnetic permeability or electrical permittivity. The metamaterial substrate can increase the performance of the near-field antenna as a whole (e.g., increase radiation efficient when compared to a substrate made from a common dielectric).

The near-field antenna further includes switch circuitry (e.g., switch **2630**, FIG. **26**) coupled to at least two of the four coplanar antenna elements. For example, the near-field antenna may include a first feed (e.g., feed **2508**-A) with opposing first and second ends, where the first end of the first feed is connected to a first of the two antenna elements composing the first dipole antenna and the second end of the first feed is connected to the switch circuitry, e.g., via metal traces deposited on a printed circuit board **2514** (FIG. **25**E).

In addition, the near-field antenna may include a second feed (e.g., feed **2508**-B) with opposing first and second ends, where the first end of the second feed is connected to a first of the two antenna elements composing the second dipole antenna and the second end of the second feed is connected to the switch circuitry, e.g., via metal traces (e.g., busing **208**) deposited on the printed circuit board **2514**. The feeds and the printed circuit board are discussed in further detail above with reference to FIG. **25**E.

The near-field antenna also includes a power amplifier (e.g., power amplifier(s) **108**, FIG. **26**) coupled to the switch circuitry (e.g., via the metal traces), and an impedance-adjusting component (e.g., component **2520**, FIG. **26**) coupled to the switch circuitry (e.g., via the metal traces). The near-field antenna may also include a controller (e.g., RF power transmitter integrated circuit **160**, FIGS. **1**A and **26**) configured to control operation of the switch circuitry and the power amplifier. The controller may be connected to the switch circuitry and the power amplifier via the metal traces. The power amplifier, the impedance-adjusting component, and the controller are discussed in further detail above with reference to FIG. **26**.

The method **3000** further includes instructing (**3004**) the switch circuitry to couple: (i) the first dipole antenna to the power amplifier, and (ii) the second dipole antenna to the impedance-adjusting component (or vice versa). For example, with reference to FIG. **26**, the integrated circuit **160** may send the "Control Out" signal to the switch circuitry **2630**, which causes one or more first switches in the switch circuitry **2630** to close and connect a respective power amplifier **108** with the first dipole antenna **2501**-A. The "Control Out" signal also causes one or more second switches in the switch circuitry **2630** to close and connect the impedance-adjusting component **2620** with the second dipole antenna **2501**-B. It is noted that, in some embodiments, the switch circuitry **2630** includes first and second switch circuits. In such embodiments, the first switch circuit is closed to connect the first dipole antenna to the power amplifier and the second dipole antenna to the impedance-adjusting component. Further, the second switch circuit is closed to connect the first dipole antenna to the impedance-adjusting component and the second dipole antenna to the power amplifier. Controlling operation of the switch circuitry **2630** is discussed in further detail above with reference to FIG. **26**.

The one or more signals generated and provided by the controller may be based on information received from a wireless-power-receiving device (e.g., receiver **104**, FIG. 2B). For example, the controller may receive location information for the wireless-power-receiving device, (ii) polarization information for a power-receiving-antenna of the wireless-power-receiving device, and/or (iii) orientation information for the wireless-power-receiving device, each of which may be received from the wireless-power-receiving device. Further, the one or more electrical signals may be based on this received information. Put another way, the controller may be configured to control operation of the switch circuitry and the power amplifier based on one or more of: (i) a location of a wireless-power-receiving device (as indicated by the location information), (ii) a polarization of a power-receiving-antenna of the wireless-power-receiving device (as indicated by the polarization information), and (iii) an orientation of the wireless-power-receiving device (as indicated by the orientation information).

As explained above with reference to FIG. **26**, the switch circuitry is configured to switchably couple the first and second dipole antennas **2501**-A, **2501**-B to the impedance-adjusting component **2620** and the power amplifier **108**, respectively (or vice versa), in response to receiving one or more electrical signals from the RF power transmitter integrated circuit **160** (e.g., the "Control Out" signal). Further, in some embodiments, the switch circuitry may be configured to switchably couple the first dipole antenna to the power amplifier and the second dipole antenna to the impedance-adjusting component when the near-field antenna is in a first operation mode. Moreover, the switch circuitry may be configured to switchably couple the second dipole antenna to the power amplifier and the first dipole antenna to the impedance-adjusting component when the near-field antenna is in a second operation mode distinct from the first operation mode.

The method **3000** further includes instructing (**3006**) the power amplifier to feed electromagnetic signals to the first dipole antenna via the switch circuitry. For example, with reference to FIG. **26**, the integrated circuit **160** sends the "RF Out" signal to the power amplifier. The power amplifier may, in turn, amplify (if needed) the received "RF Out" signal, and then provide the amplified RF signal to the first dipole antenna via the switch circuitry. The electromagnetic signals, when fed to the first dipole antenna, cause the first dipole antenna to radiate electromagnetic signals to be received by the wireless-power-receiving device, which is located within a threshold distance from the near-field antenna. The wireless-power-receiving device can use energy from the radiated electromagnetic signals, once received, to power or charge an electronic device coupled with the wireless-power-receiving device. Additionally, because the second dipole antenna is connected to the impedance-adjusting component and the first dipole antenna is not, an impedance of the second dipole antenna is adjusted (by the impedance-adjusting component) so that the impedance of the second dipole antenna differs from an impedance of the first dipole antenna. In such an arrangement, the first dipole antenna and the second dipole antenna are detuned (e.g., an operating frequency of the first dipole antenna differs from an operating frequency of the second dipole antenna).

In some embodiments, the method **3000** further includes reflecting, by the reflector, at least a portion of the electromagnetic signals radiated by the first dipole antenna. In addition, in some embodiments, the method **3000** further includes cancelling, by the reflector, at least a portion of the electromagnetic signals radiated by the first dipole antenna.

All of these examples are non-limiting and any number of combinations and multi-layered structures are possible using the example structures described above.

Further embodiments also include various subsets of the above embodiments including embodiments in FIGS. **1**-**30** combined or otherwise re-arranged in various embodiments, as one of skill in the art will readily appreciate while reading this disclosure.

The terminology used in the description of the invention herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used in the description of the invention and the appended claims, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, steps, operations, elements, components, and/or groups thereof.

It will also be understood that, although the terms "first," "second," etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first region could be termed a second region, and, similarly, a second region could be termed a first region, without changing the meaning of the description, so long as all occurrences of the "first region" are renamed consistently and all occurrences of the "second region" are renamed consistently. The first region and the second region are both regions, but they are not the same region.

The foregoing description, for purpose of explanation, has been described with reference to specific embodiments. However, the illustrative discussions above are not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. An electronic device for receiving near-field wireless power, comprising:

a receiver including one or more receiving antenna elements formed by respective conductive lines in a meandering pattern, each receiving antenna element configured to receive one or more near-field radio-frequency signals radiated from a transmitting antenna element of a near-field power transmitter, wherein:

the one or more receiving antenna elements are configured to receive the one or more near-field radio-frequency signals radiated from the transmitting antenna element of the near-field power transmitter when the electronic device is on a surface of the near-field power transmitter, and the transmitting antenna element is formed by respective conductive lines in a meandering pattern;

the transmitting antenna element is selectively activated from among a plurality of available transmitting antenna elements of the near-field transmitter based on a determination that an amount of energy transferred to the receiver via the one or more near-field radio-frequency signals is above a predetermined energy-transfer threshold; and

a power-harvesting circuit of the receiver, the power harvesting circuit configured to convert the one or more near-field radio-frequency signals received from the transmitting antenna element of the near-field power transmitter into usable power for the electronic device.

2. The electronic device of claim **1**, wherein the predetermined energy-transfer threshold is a percentage of energy transfer from the power transmitter to the receiver of at least 75%.

3. The electronic device of claim **1**, wherein the predetermined energy-transfer threshold is a percentage of energy transfer from the power transmitter to the receiver of at least 98%.

4. The electronic device of claim **1**, wherein the usable power is provided to an energy storage device of the electronic device.

5. The electronic device of claim **1**, wherein the one or more receiving antenna elements include a first receiving antenna element and a second antenna element, the first and second receiving antenna elements having the same meandering pattern.

6. The electronic device of claim **1**, wherein the one or more receiving antenna elements include a first receiving antenna element and a second antenna element, the first and second receiving antenna elements having distinct meandering patterns.

7. The electronic device of claim **1**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements have the same meandering pattern.

8. The electronic device of claim **1**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements have distinct meandering patterns.

9. The electronic device of claim **1**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements are positioned at different locations of the power transmitter.

10. The electronic device of claim **1**, wherein the near-field power transmitter is configured to selectively activates the transmitting antenna element via one or more switches, the one or more switches coupled between the transmitting antenna element and a power amplifier of the near-field power transmitter, and the one or more switches are configured to provide power from the power amplifier to the transmitting antenna element.

11. The electronic device of claim **10**, wherein the one or more switches are coupled to a controller of the near-field power transmitter, and the controller is configured to control operation of the one or more switches and the power amplifier.

12. The electronic device of claim **10**, wherein at least two transmitting antenna elements are configured to be selectively activated based on the position of the receiver in relation to near-field the power transmitter.

13. The electronic device of claim **1**, wherein the receiver is externally coupled to the electronic device.

14. The electronic device of claim **1**, wherein the receiver is internally coupled to the electronic device.

15. The electronic device of claim **1**, wherein the electronic device is selected from the group consisting of: smartphones, tablets, laptops, earbuds, and connected devices.

16. The electronic device of claim **1**, wherein the one or more receiving antenna elements are monopole antennas.

17. A method of providing wireless power to an electronic device, comprising:

receiving, at a receiver of the electronic device, one or more near-field radio-frequency signals radiated from a transmitting antenna element of a near-field power transmitter, wherein:

the receiver includes one or more receiving antenna elements formed by respective conductive lines in a meandering pattern, each receiving antenna element configured to receive the one or more near-field radio-frequency signals radiated from the transmitting antenna element of the near-field power transmitter,

the one or more receiving antenna elements are configured to receive the one or more near-field radio-frequency signals radiated from the transmitting antenna element of the near-field power transmitter when the electronic device is on a surface of the near-field power transmitter, and the transmitting antenna element is formed by respective conductive lines in a meandering pattern; and

the transmitting antenna element is selectively activated from among a plurality of available transmitting antenna elements of the near-field transmitter based on a determination that an amount of energy transferred to the receiver via the one or more near-field radio-frequency signals is above a predetermined energy-transfer threshold;

converting, via a power-harvesting circuit of the receiver, the one or more near-field radio-frequency signals received from the transmitting antenna element of the near-field power transmitter into usable power for the electronic device; and

providing the usable power to the electronic device.

18. A system for charging an electronic device using wirelessly delivered power, the system comprising:

the electronic device including a receiver with one or more receiving antenna elements formed by respective conductive lines in a meandering pattern, each receiving antenna element configured to receive one or more near-field radio-frequency signals radiated from a transmitting antenna element of a near-field power transmitter, wherein:

the one or more receiving antenna elements are configured to receive the one or more near-field radio-frequency signals radiated from the transmitting antenna element of the near-field power transmitter when the electronic device is on a surface of the near-field power transmitter, and the transmitting antenna element is formed by respective conductive lines in a meandering pattern; and

a power-harvesting circuit of the receiver converts the one or more near-field radio-frequency signals received from the transmitting antenna element of the near-field power transmitter into usable power for the electronic device; and

the near-field transmitter, wherein the near-field transmitter is configured to selectively activate the transmitting antenna element from among a plurality of available transmitting antenna elements of the near-field transmitter based on a determination that an amount of energy transferred to the receiver via the one or more near-field radio-frequency signals is above a predetermined energy-transfer threshold.

19. The system of claim **18**, wherein the predetermined energy-transfer threshold is a percentage of energy transfer from the power transmitter to the receiver of at least 75%.

20. The system of claim **18**, wherein the predetermined energy-transfer threshold is a percentage of energy transfer from the power transmitter to the receiver of at least 98%.

21. The system of claim **18**, wherein the usable power is provided to an energy storage device of the electronic device.

22. The system of claim **18**, wherein the one or more receiving antenna elements include a first receiving antenna element and a second antenna element, the first and second receiving antenna elements having the same meandering pattern.

23. The system of claim **18**, wherein the one or more receiving antenna elements include a first receiving antenna element and a second antenna element, the first and second receiving antenna elements having distinct meandering patterns.

24. The system of claim **18**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements have the same meandering pattern.

25. The system of claim **18**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements have distinct meandering patterns.

26. The system of claim **18**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements are positioned at different locations of the power transmitter.

27. The system of claim **18**, wherein the near-field power transmitter is configured to selectively activate the transmitting antenna element via one or more switches, the one or more switches coupled between the transmitting antenna element and a power amplifier of the near- field power transmitter, and the one or more switches are configured to provide power from the power amplifier to the transmitting antenna element.

28. The system of claim **27**, wherein the one or more switches are coupled to a controller of the near-field power transmitter, and the controller is configured to control operation of the one or more switches and the power amplifier.

29. The system of claim **27**, wherein at least two transmitting antenna elements are configured to be selectively activated based on the position of the receiver in relation to the near- field power transmitter.

30. The system of claim **18**, wherein the receiver is externally coupled to the electronic device.

31. The system of claim **18**, wherein the receiver is internally coupled to the electronic device.

32. The system of claim **18**, wherein the electronic device is selected from the group consisting of: smartphones, tablets, laptops, earbuds, and connected devices.

33. The system of claim **18**, wherein the one or more receiving antenna elements are monopole antennas.

34. The method of claim **17**, wherein the predetermined energy-transfer threshold is a percentage of energy transfer from the power transmitter to the receiver of at least 75%.

35. The method of claim **17**, wherein the predetermined energy-transfer threshold is a percentage of energy transfer from the power transmitter to the receiver of at least 98%.

36. The method of claim **17**, wherein providing the usable power to the electronic device includes providing the usable power to an energy storage device of the electronic device.

37. The method of claim **17**, wherein the one or more receiving antenna elements include a first receiving antenna element and a second antenna element, the first and second receiving antenna elements having the same meandering pattern.

38. The method of claim **17**, wherein the one or more receiving antenna elements include a first receiving antenna element and a second antenna element, the first and second receiving antenna elements having distinct meandering patterns.

39. The method of claim **17**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements have the same meandering pattern.

40. The method of claim **17**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements have distinct meandering patterns.

41. The method of claim **17**, wherein at least two transmitting antenna elements of the plurality of available transmitting antenna elements are positioned at different locations of the near-field power transmitter.

42. The method of claim **17**, wherein the near-field power transmitter selectively activates the transmitting antenna element via one or more switches, the one or more switches coupled between the transmitting antenna element and a power amplifier of the near-field power transmitter, and the one or more switches are configured to provide power from the power amplifier to the transmitting antenna element.

43. The method of claim **42**, wherein the one or more switches are coupled to a controller of the near-field power transmitter configured, and the controller is configured to control operation of the one or more switches and the power amplifier.

44. The method of claim **42**, wherein at least two transmitting antenna elements are selectively activated based on the position of the receiver in relation to the power transmitter.

45. The method of claim **17**, wherein the receiver is externally coupled to the electronic device.

46. The method of claim **17**, wherein the receiver is internally coupled to the electronic device.

47. The method of claim **17**, wherein the electronic device is selected from the group consisting of: smartphones, tablets, laptops, earbuds, and connected devices.

48. The method of claim **17**, wherein the one or more receiving antenna elements are monopole antennas.

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